The Confluence of Digital Design/Fabrication and Biological Principles

Systematic knowledge transfer for the development of integrated architectural systems

by

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Abstract

In the last century, many of the developed computational theories and methods have been inspired by biological principles. The design generation methods, originating from these theories, along with the advances in digital fabrication technologies have impacted architecture in the last thirty years. One of the main qualities of the biological systems, functional integrity, can be adapted to architectural systems to shape a new generation of digitally designed and fabricated architectural systems. Proposing a guideline for the development of integrated systems, this thesis first presents a critical review on the precedents of biologically inspired computational theories, form generation tools and digital fabrication techniques. Later, it frames a systematic cross-domain knowledge transfer method, specifically with some guidelines for the development of architectural integrated systems. And finally through an example, it has been demonstrated how the described process can lead to the development of a method for the design and fabrication of an integrated wall system.

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1. Introduction

Since the emergence of computational theories and methods about half a century ago, the influence of extracted principles from natural systems has been ubiquitous in the design and computation domain. These biologically inspired computational methods along with the advances in CAD/CAM technologies have impacted architecture, first, by introducing computational form-generation techniques and, later, by engaging digital fabrication technologies to embody these forms in physical matters.

Learning from natural models, one of the fundamental aspects of all biological systems is functional integrity, both in their performance and interaction with the environment. Biological organisms from cell level to the complex structure of the whole body intrinsically perform different functions concurrently. On the other hand, most of the current research on applications of CAD/CAM technologies has been focused on solving one specific problem at a time. Although this concentration on subjects such as geometry, structure, assembly and materials is essential for the progress of these fields, the missing link is the combination of these elements in a unified system, necessary for the development of architectural components.

Analogous to the development of computational theories in 60s and 70s, taking advantage of biological concepts is applicable to the current issue on the development of integrated systems in digitally designed and fabricated architecture. Consequently, this research emphasizes the development of multi-functional architectural components as integrated and responsive systems both in the design and fabrication phases by analyzing and learning from underlying functional principles of biological models.

First, this thesis reviews the impacts of biological principles on the past and present breakthroughs in computation and CAD/CAM technologies and applications. Later, the research presents the core ideas on the integration of functions in biological models, which overlap with architectural systems and thus can be extracted and emulated in digital design and fabrication. Later it discusses the fundamental elements for a systematic cross-domain transfer of knowledge from biology to computational design, illuminates the major obstructions in analysis and synthesis of features between these domains, and suggests some guidelines that give a better understanding on the extraction of biological principles for the design and fabrication domain. Finally, the research proposes a concept method for the development of an integrated system in design and fabrication. This example focuses on the design and fabrication of a wall panel system with different functional requirements, and draws inspiration from cell level structures for the development of a computational design and fabrication method.

2. Problem definition: The need for the development of integrated systems

This chapter argues for the necessity for the development of functional *integrated* systems: functions that are expected from any architectural systems, and particularly digitally fabricated systems. These factors include structural stability, transparency/opacity, material behavior, thermal insulation and water resistance. Despite great advances in digital technologies, which permit the incorporation of responsive and smart digital technologies into conventional architectural systems, many of the functional criteria mentioned have remained constant in architecture because of unchanging basic human needs. In the last decade, a great deal of research has been concentrated on the embodiment of complex architectural forms by using digital design and fabrication technologies, each of which addresses a single problem at a time. The current research focuses on the combination and interaction of different functions in a single architectural component such as a wall panel, and suggests an *integrated* approach in which each of the functional sub-systems acts as a part of the whole and in a close simultaneous relation with the other elements.

The following presents the role of integrated multi-functionality in natural organisms, comparing it with the same topic in architecture, and then in digital design and fabrication.

2.1. Integrated systems in natural organisms

Natural organisms are able to perform different functions simultaneously. Each of their body organs is formed in complete unity with organ functions and in close correlation with the whole body. These functional parts act inseparably because of their effect on each other. D'Arcy Thompson in his seminal book, *On Growth and Form*, discusses functional integrity in natural organisms. He states that different parts of the whole body are related to each other through strong functional correlations. He notes that although researchers are aware of the close relation among different parts of an organism, they tend to untangle the intricacies of a complex study by separating the body to separate entities. Thompson adds that by analyzing an organism as separate parts or properties, we magnify their independence, which may cause the concealment of the principles that lie behind the integrity of the composite whole. Researchers study different parts of an organism independently because of our lack of ability to comprehensively understand the complex systems.

He writes:

> " ... as biologists, we may go so far as to say that even bones themselves are only limited and even a deceptive sense, separate and individual things. The skeleton begins as a continuum, and a continuum it remains all life long. The things that link bone with bone, cartilage, ligaments,

membrane, are fashioned out of the same primordial tissue, and come into being pari passu with the bones themselves. The entire fabric has its soft parts and its hard, its rigid and its flexible parts, but until we disrupt and dismember its bony, gristly and fibrous parts, one from another, it exists simply as a 'skeleton', as one integral and individual whole." [1]

Here, he brings up two main issues: first, all different organs with different properties and functions, such as bones and muscles, closely correlate with each other; and second, they originated from the same "primordial tissue." In his own words "they come into being together and act and react together." [2]

2.2. Integrated systems in architecture

As the most basic definition of architecture, buildings are designed and built to fulfill certain functions. [3]

Thompson compares the way that human-built entities and biological models work as an integrated whole through an example of a 'bridge' and a 'body skeleton'. He mentions that the identity of man-made objects, like biological organisms, resulted from the integration of all their parts. The pillars, rods and rivets of a bridge should not be recognized as separate entities; rather they should be understood as a complete unity in which all the parts are functionally related to each other.

Through a more detailed investigation into the integrity of architecture, Mitchell in *The Logic of Architecture* states that elements in architectural compositions often play different roles at the same time. For example windows should allow light penetration and prevent heath loss at the same time. However, such functional requirements may not necessitate the same formal expressions. In many situations, the optimum formal solution for one function is in contradiction to the other. To manipulate this contradiction in the design of multi-functional elements in architectural systems, the most common method is a trade-off solution. Mitchell suggests an improved substitute solution in which the optimal performance in one aspect does not result in the degradation of other aspects.[4] This idea refers to the specialization of organs in highly evolved natural organisms, such as mammals and birds. In these organisms the number of body parts is reduced, but each of them performs several highly specialized functions, as it can be seen in comparing the number of legs in a millipedes and a mammal. According to Darwin's theory of natural selection, the number of parts is decreased in organisms during evolution because of the changes in living patterns.[5] "It is also a law in evolution that the parts in an organism tend toward reduction in number, with the fewer parts greatly specialized in function".[6] As Mitchell asserts, the same process exists in architecture. He compares three famous historical domes with similar functions, to enclose interior space, provide lighting for the inner space and perform as a city landmark. This comparison shows the progress of "functional articulation" and "optimal specialization of the elements".[7]

2.3. Integrated systems in digital architecture

The emergence of digital design and fabrication has provided designers with new techniques and machines, which enable them not only to design complex forms and geometries but also to embody them. However, functional criteria in architecture have remained unaltered. According to the ongoing developments in computational design and fabrication, most of the current research conducted in these topics has been focused on solving a single problem at a time, issues such as geometry, structure, assembly, and materials. However, the development of integrated design generation models in computational architecture has gained a high priority in this field.[8] Architects seek new solutions to develop integrated systems by means of digital technologies: "As Structural, chemical and computational properties are integrated at nano-, micro-, and macro-scales, even the most traditional materials might become dynamic."[9]

Since the complex integrated systems exist and function successfully in all natural organisms, drawing analogy to biological models provides deeper insight for the development of functionally integrated architectural systems.

Notes

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1 . D'Archy Thampson, *On Growth and Form* (New York: Cambridge University Press, 2008), 263.

2 . Ibid., 263.

3 . William J. Mitchell, *The Logic of Architecture: Design, Computation, and Cognition*, (Cambridge: The MIT Press, 1990), 219.

4 . Ibid., 226.

5 . D'Archy Thampson, *On Growth and Form* (New York: Cambridge University Press, 2008), 264.

6 . Samuel W. Williston, *Water Reptiles of the Past and Present* (Chicago: University of Chicago Press, 1914).

7 . William J. Mitchell, *The Logic of Architecture: Design, Computation, and Cognition*, (Cambridge: The MIT Press, 1990), 226.

8 . Rivka Oxman, "Performative design: a performance-based model of digital architectural design," *Environment and Planning B: Planning and Design* (2009): 1.

9 . Ramia Maze, *Occupying Time: Design, technology and the form of interaction* (Sweden: Axl Books, 2007), 35.

3. A critical review of precedents on the application of biological principles in computation and CAD/CAM technologies

This chapter presents a background review of the confluence of biological principles and architecture, focusing on digital design and fabrication in particular. The influence of ideas, derived from nature, has been pervasive throughout the history of architecture. Just in the last century many different projects, methods and theories have been inspired and designed based on forms, structures, systems and processes in nature. However, a comprehensive categorization and analysis of these methods does not exist.

Thus, this thesis offers a new perspective on biologically inspired digital design and fabrication systems. And relatively seeks to map the position of a functionally *integrated* system, developed by digital design and fabrication technologies. A timeline is created in which some general trends can be identified in the most influential biologically inspired projects of the last century. Based on the focus of this research, digital design and fabrication, these projects are categorized into three major groups: computational theories, computational form generation methods and tools, and finally, structural and digital fabrication techniques and processes.

The first group includes some of the most prominent computational theories of our time that were inspired by biological principles, theories such as Artificial Neural Networks (1943), Cellular Automata (1940s), Genetic Algorithms (1960s), and L-systems (1968). Although initiated in the 1940s, these theories were mainly developed in the 1960s and 1970s along with the technological progresses in hardware and electronic devices. These biologically inspired computational theories were utilized in artificial intelligence and in robotics as well as in their later applications in the development of computational design generation tools.

In the last decade of the 20th century, these biologically inspired *computational theories* made the foundations for a great deal of research on the form generation techniques and tools, which were based on the theories such as cellular automata, genetic algorithms and L-systems. These methods were pioneered and promoted by designers and scientists such as John Frazer (1995), Makoto Watanabe (1995), Michael Rosenman and John Gero (1996), and Martin Hemberg, Una-May O'Reilly and Peter Testa (2001).

Biological organisms also have greatly inspired *structural and fabrication systems* in architecture. In the 1940s and 1950s, architects and engineers such as Buckminster Fuller, Frei Otto and Fred Severud effectively analyzed many natural organisms and extracted the structural and material principles. Frei Otto and his team at the Institute of Lightweight Structures especially did extensive research on different organisms, the results of which have been applied on the development of pneumatic, tensile and shell structures, all published in IL series.

However, these studies on structure, form and material in the 40s and 50s were not combined with computational form generation methods until to the development of CAM and digital fabrication machineries in the first decade of 21st century. The new subtractive and additive digital manufacturing machines such as laser cutters, computer numerically controlled machines (CNC), water jet cutters, and rapid prototyping have prepared the ground for the work of the new generation of computational designer-fabricator architects, who extract the essence of natural systems and apply it to their work. Pioneers such as Michel Hensel, Achim Menges and Michael Weinstock[1] established Emergent Technologies and Design discipline group at Architectural Association in London. They promote a new approach to architecture practice that defines an interrelationship between design concepts, such as emergence and self-organization, and the latest technologies in design, manufacturing and construction. Engaging digital design and fabrication technologies and designing based on ideas derived from natural world, designers such as Neri Oxman (Materialecology), Jennie Sabin and Peter Lloyd Jones (Lab Studio), Andrew Kudless (Matsys), Tom Wiscombe (EMERGENT) and Chris Bosse are shaping the frontiers of a new paradigm in architecture.

The biologically inspired designs that combine computational theories, design generation methods and fabrication technologies, nevertheless, need to consider the combination and interaction of different functions in their systems. Moreover, the new advances in digital technologies facilitate the development of *integrated* systems, both in design and fabrication phases. The integrated systems that are inspired by biological phenomena can be embodied by computational methods, which themselves are developed based on biological principles (Figure 3.1).

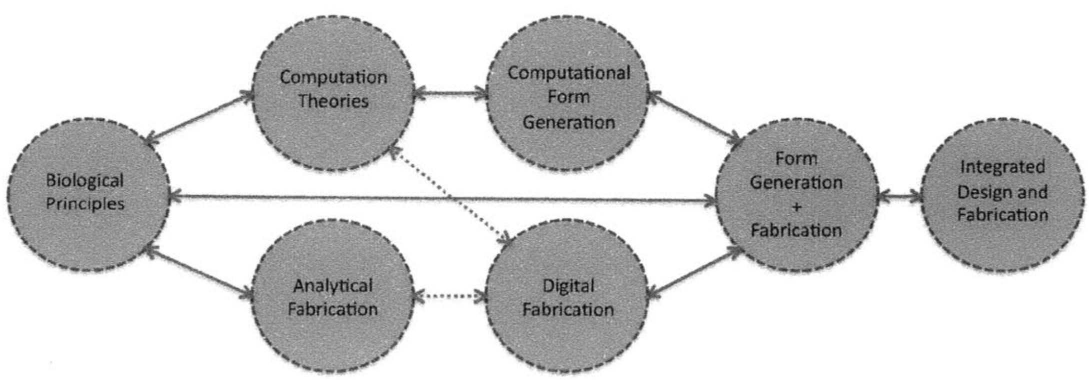

Figure 3.1. Biological principles, and computation theories, digital fabrication and form generation

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3.1. Biological principles and computational theories

This section presents computational theories that are inspired by biological analogies. Most of these methods have found later design generation and fabrication applications in architecture. These design methods will be discussed in the future sections.

1940s - Cellular Automaton

Cellular automaton is a mathematical and computational system developed by John von Neumann, Stanislaw Ulam, and Nils Barricelli.[1] This system proposes mathematical models for self-organizing systems, including complex systems in nature such as snowflakes, patterns of flow in turbulent fluids, and biological systems. These systems have open interaction with their environment and transform from disordered to relatively ordered conditions over time. Although Cellular automaton uses comparatively simple mathematical methods for analysis, they can explain and generate models for a wide range of complicated phenomena. These models are able to characterize a variety of physical, chemical, biological, and other systems.[2] Cellular automaton consists of a regular grid of cells with an initial finite number of states such as "on" or "off." The state of the cell changes through a number of time steps based on a set of rules and according on the states of the neighboring cells. This process can be repeated for desired number of time steps. Different sets of rules with different complexities can produce intricate patterns, often unpredictable from the initial conditions.[3]

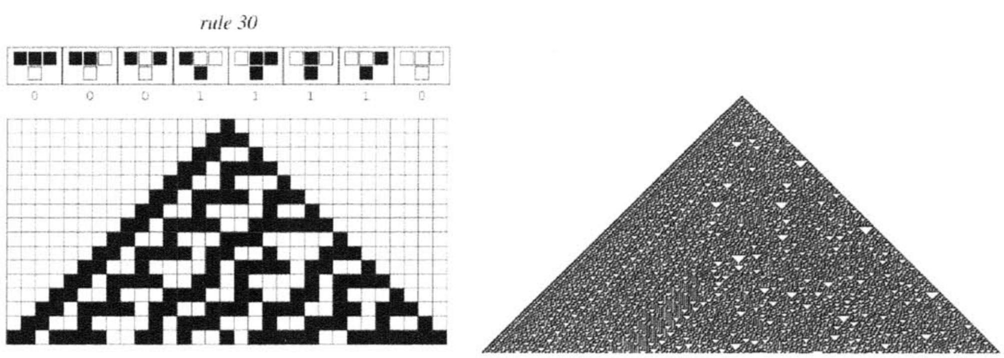


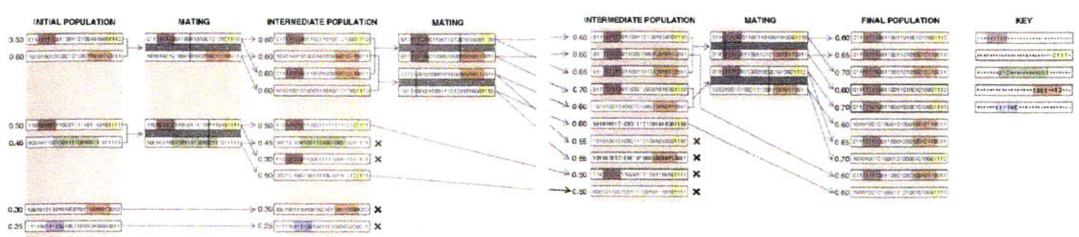
Figure 3.2. Rule 30 cellular automaton

1960s - Genetic algorithm and evolutionary computation

Genetic algorithm (GA) is a computational procedure, inspired by natural evolution, which represents concepts comparable to *individuals, mating, chromosome crossover, gene mutation, fitness,* and *natural selection*.[4] In the 1960s, John Holland proposed the idea of genetic algorithm for the first time. Here he describes his source of inspiration:

> "Living organisms are consummate problem solvers. They exhibit a versatility that puts the best computer programs to shame. This observation is especially galling for computer scientists, who may spend months or years of intellectual effort on an algorithm, whereas organisms come by their abilities through the apparently undirected mechanism of evolution and natural selection." [5]

Genetic algorithms are based on two major concepts in the process of evolution: *natural selection*, which specifies the survival of the fittest members of a population, and *sexual reproduction* that provides mixing and rearrangement of genes in children. [6] Accordingly, the proposed concept for a problem-solving computer program with a generative algorithm consists of a set of rules that will be applied to possible solutions in a given *population.* Individuals as the members of this population tend to pass on their traits to their children to shape a new generation. However, based on *mutation*, children's genes are slightly different from their parents'. It is also possible that children inherit genes from different parents, similar to *sexual reproduction*. The fittest individuals, indicated by an evaluation process, tend to produce more offspring, which leads to a population with more favorable traits (Figure 3.3). [7 8]



GENE POOL of algorithms consists of strings of 1's and 0's. Each string is evaluated for fitness, and the best strings mate (*second column*) and produce offspring by means of crossover (*indicated by a vertical black line*). Strings of intermediate fitness simply survive to the next generation, and the least fit perish. If particular patterns of bits (*shown here by colored areas*) improve the fitness of strings that carry them, repeated cycles of evaluation and mating (*succeeding columns*) will cause the proportion of these high-quality "building blocks" to increase. The pattern corresponding to each building block appears in the rightmost column; asterisks represent bits whose values are unspecified.

Figure 3.3

1968 - L-system

L-system (the Lindenmayer system) is a string-rewriting algorithm[9] introduced by botanist Aristid Lindenmayer in 1968. This system has been proposed to describe the growth of living organisms. [10] The topology of growing structures, such as branches and leaves, can be described by this rule-based system. In L-system, a string of symbols as the initial state of the process is accompanied by a set of rules, which performs a recursive substitution of symbols with symbol strings. L-system symbols can represent parameters such as length and angle of branches, leaves, and flowers. [11] In this system, the underlying principles of theoretical biology have formed a powerful generative computer system, which has been utilized in many design-generating tools and techniques in computational design.

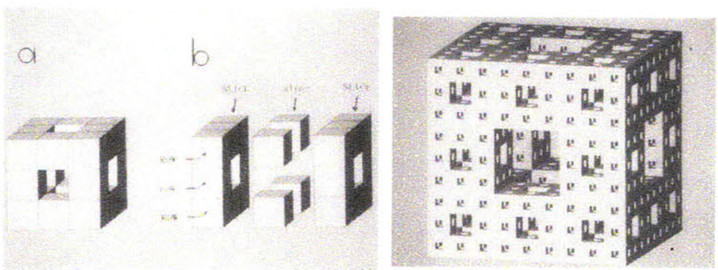


Figure 3.4 Construction of the Menger sponge, a three-dimensional fractal model

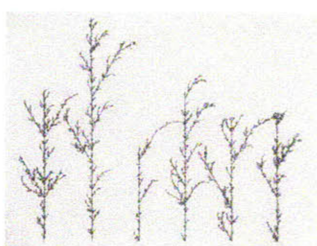


Figure 3.5. Computer generated leaves with L-system algorithm

1943 - Artificial Neural Network

Artificial Neural Network is a computational model for information processing that has been inspired by the functional behavior of biological neural networks. Composed of a set of interconnected artificial neurons, it solves problems by simultaneous information processing. [12] Biological neural nets consist of synapses, axons, dendrites and cell bodies and artificial neural networks mimic their process of multi-connection and threshold level triggering in form of simulated neurons with multipliers, adders and thresholds.[13] Neural networks are adaptable systems and can learn through a training process, which is useful for applications such as pattern recognition or data classification. The first artificial neuron was proposed by neurophysiologist Warren McCulloch and the logician Walter Pits in 1943. Their model networks, based on their assumptions of biological system, were considered to be binary devices with fixed thresholds. However, technical limitations prevented its realization till the 1960s. [14]

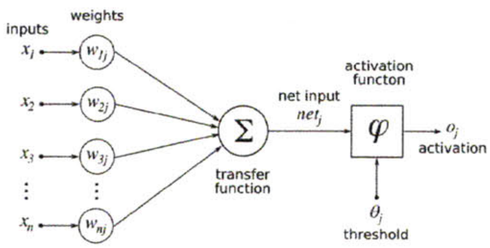


Figure 3.6

1975 - Fractal Theory

Fractals are defined as: "any of various extremely irregular curves or shapes for which any suitably chosen part is similar in shape to a given larger or smaller part when magnified or reduced to the same size." [15] Fractal geometry, which builds on the work of mathematicians like Felix Hausdorff, for the first time was termed by Benoit B. Mandelbrot in 1975. This theory provides a powerful tool in applied mathematics with the ability to model variety of phenomena from physical objects to the behavior of the stock market. Fractal geometry provides a system for the mathematical study of shapes with never-ending, self-similar, meandering details. Fractal shapes are associated with self-similarity, which represents the resemblance of parts to the whole in a recursive manner. Thus, natural shapes such as leaves, tree branching, mountain ridges, flood levels of a river, wave patterns, and nerve pulses, can be explained by this system of geometry.[16,17]

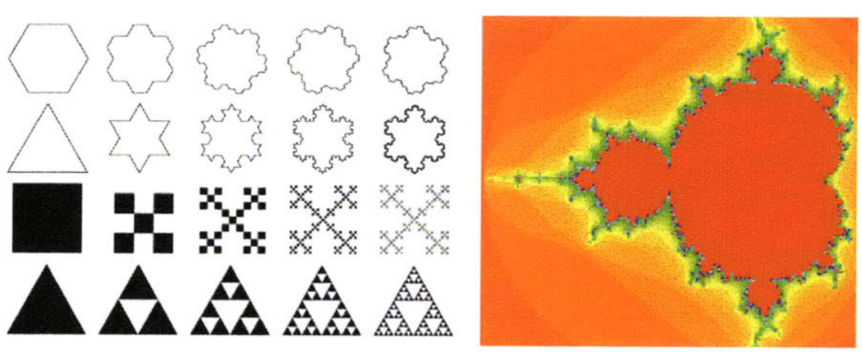


Figure 3.7 From http://mathworld.wolfram.com/Fractal.html

1986 - Artificial Life (A-Life)

Artificial life (A-Life) is a discipline that takes advantage of computer simulation and information concepts for the study and simulation of life and living systems. A-Life was coined by computer scientist, Christopher Langton, in 1986. Langton characterized artificial life as "locating life-as-we-know-it within the larger picture of life-as-it-could-be". [18] Describing this in more detail Langton states:

> "A-life complements the analytic approach of traditional biology with a synthetic approach: rather than studying biological phenomena by taking living organisms apart to see how they work, we attempt to put together systems that behave like living organisms."[19]

The interdisciplinary essence of A-Life engages different fields such as biology, artificial intelligence, computational psychology, mathematics, physics, biochemistry, immunology, economics and philosophy. On the theoretical level, A-Life focuses on self-organization of living things in which higher degree of order is developed by interaction among simple and less ordered members. [20]

1989 - Swarm Intelligence

Swarm Intelligence is defined as the emergent collective intelligence of groups of simple agents that have decentralized and collective behaviors. [21] The concept has been termed by Gerardo Beni and Jing Wang in 1981.[22] Swarm intelligence has been inspired by social insects and animals such as ants, bees, wasps, termites and birds. The swarm intelligence principle relies on autonomy, emergence and distributed functioning rather than control, preprogramming and centralization. The application of this method ranges from the routing of traffic in telecommunication networks to the design of control algorithms for a group of autonomous robots.[23]

Figure 3.8. Flock of starlings

Figure 3.9. Swarm robotics

3.2. Biological principles and computational form generation methods

1995 - John Frazer/ Evolutionary Architecture

John Frazer as one of the groundbreakers of computational form generation, proposed the idea of *Evolutionary Architecture,* which was initiated from his diploma project in 1969 and further developed between 1989 and 1996 in Architectural Association, London. He bases his research on the works of Gordon Pask, the cybernetic pioneer in the 1960s. Using computational theories such as cellular automata and genetic algorithm, Frazer investigates the form-generating processes in architecture. As Gordon Pask describes, the fundamental thesis of the Evolutionary Architecture is: "architecture as a living, evolving thing."[24] Treating architecture as a form of artificial life, Frazer suggests computer scripts that can act as genetic representation of architecture in form of DNA. These architectural computer genes can develop in an evolutionary process in response to the conditions defined by the user and environment. The evolutionary architecture was developed to imitate symbiotic behavior and metabolic balance of natural environment (Figure 3.10).[25] [26]

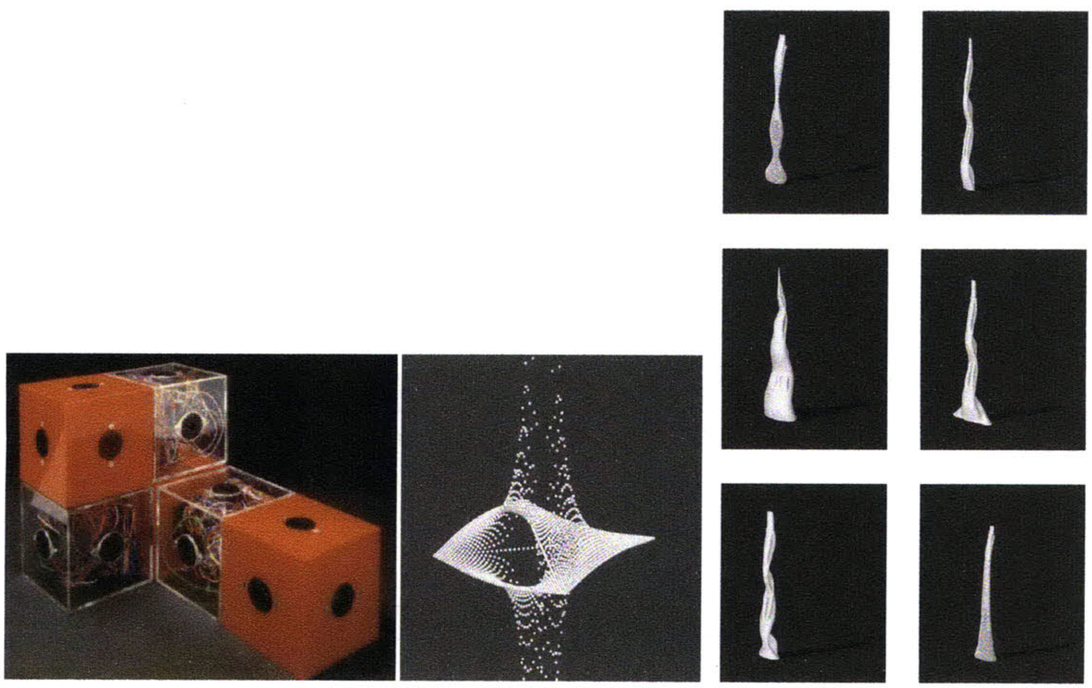


Figure 3.10

1996 - Michael Rosenman and John Gero

Michael Rosenman and John Gero have worked on methods for evolutionary architecture in the 1990s at the University of Sydney. Their research focuses on evolving designs by generating useful complex gene structures. Their work is specifically concentrated on generating architectural floor plans by organizing different rooms in the overall layout of the house. They acquired different methods such as evolving complex gene structures from a given population of design solutions or using a hierarchical growth approach. [27] These methods create building blocks as individual components of a higher-level component assembly. Rather than organizing the productive genes of the algorithm into a single string, as one chromosome, which impedes the evolution process, they define different hierarchical level of the design process, each of them containing its own design chromosomes. As Rosenman describes it: " In a flat model of form generation, a genotype will consist of a string of a very large number of basic genes. In a hierarchical model, there are a number of components chromosomes, at different levels, consisting of much shorter strings of genes, which are the chromosomes at the next lower level. All in all, the total number of genes will be the same in the flat and hierarchical models." [28] (Figure 3.11, 3.12)

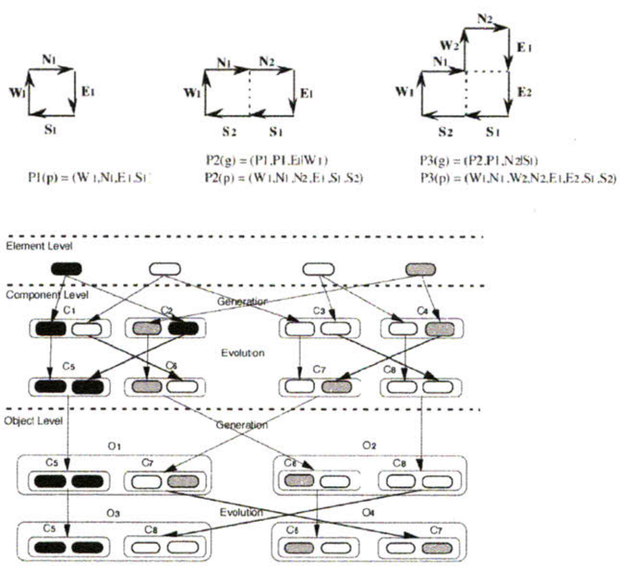


Figure 3.11

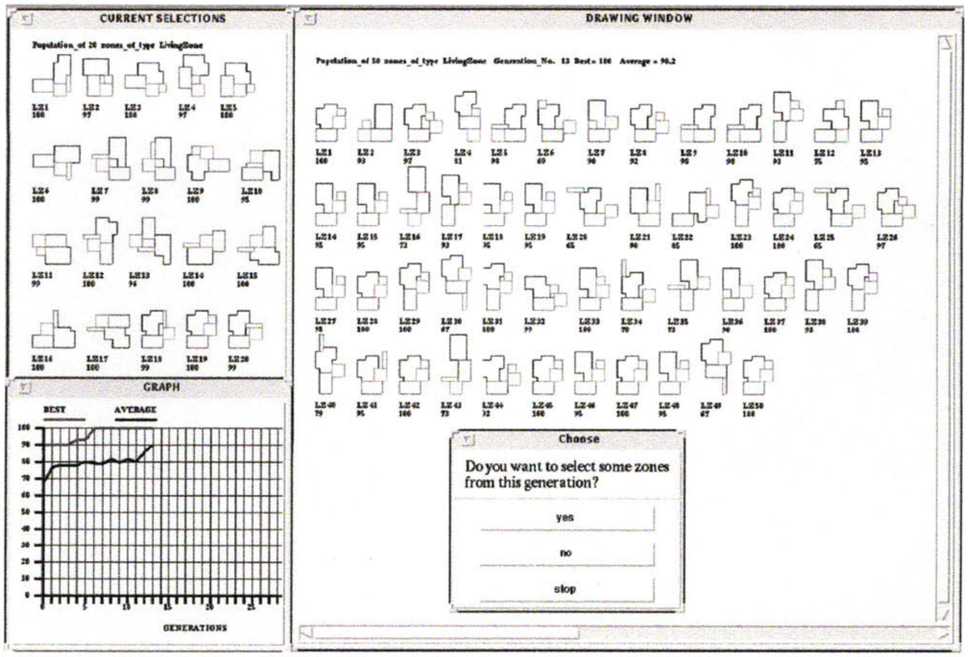


Figure 3.12

2001 - Martin Hemberg, Una-May O'Reilly and Peter Testa/ Genr8

Computer scientists, Martin Hemberg and Una-May O'Reilly in collaboration with designer, Peter Testa from the Emergent Design Group at MIT, have developed a computational design tool, named Genr8, to apply ideas from Artificial Life and evolutionary computing to the domain of architecture. Their approach to form generation is based on the process of growth and evolution, as it exists in nature. Architects can design creative three-dimensional digital surfaces and forms by using this design tool, which performs based on generative processes. The technical aspects of this tool were founded on two major concepts: evolutionary search and HEMLS (Hemberg Extended Map L-Systems). HELMS' methods enable a growth engine to execute and visualize a set of growth instructions, embedded in the system and modified by the user. The developers of this tool compare the forms that were grown by this engine with the growth of a leaf from its primitive cells. As this leaf shapes in response to environmental factors such as gravity and sunlight, the forms created with Genr8 grow in reaction to an environment of digital boundaries and attractors. [29] [30] (Figure 3.13, 3.14)

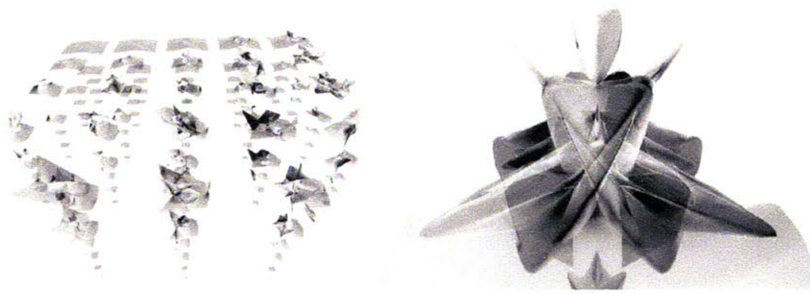


Figure 3.13

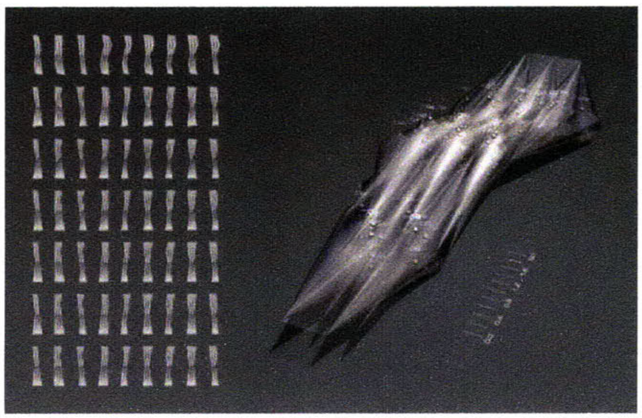


Figure 3.14

3.3. Biological principles and fabrication and structural applications

2004 - Michael Hensel, Achim Menges and Michael Weinstock

The founders and directors of Emergent Technologies and Design discipline group at Architectural Association in London, Michael Hensel, Achim Menges and Michael Weinstock, introduce new methods to conceive, design and produce architecture. They have explored concepts such as *Emergence*, *Morphogenetic* and *Morpho-Ecologies*.

Emergence as an important new concept in artificial intelligence, information theory, digital technology, economics, climate studies, material science and biometric engineering is the focal point of their research and educational system. They define *emergence* as: "the process by which new and coherent structures, patterns and properties 'emerge' from within complex systems." These architects consider architectural structures as complex energy and material systems. In this process, the design shapes, evolves and behaves as part of an environment and in correlation with other active systems. They highly incorporate architectural design with construction and manufacturing processes, utilizing computational and practical methods. [31] [32]

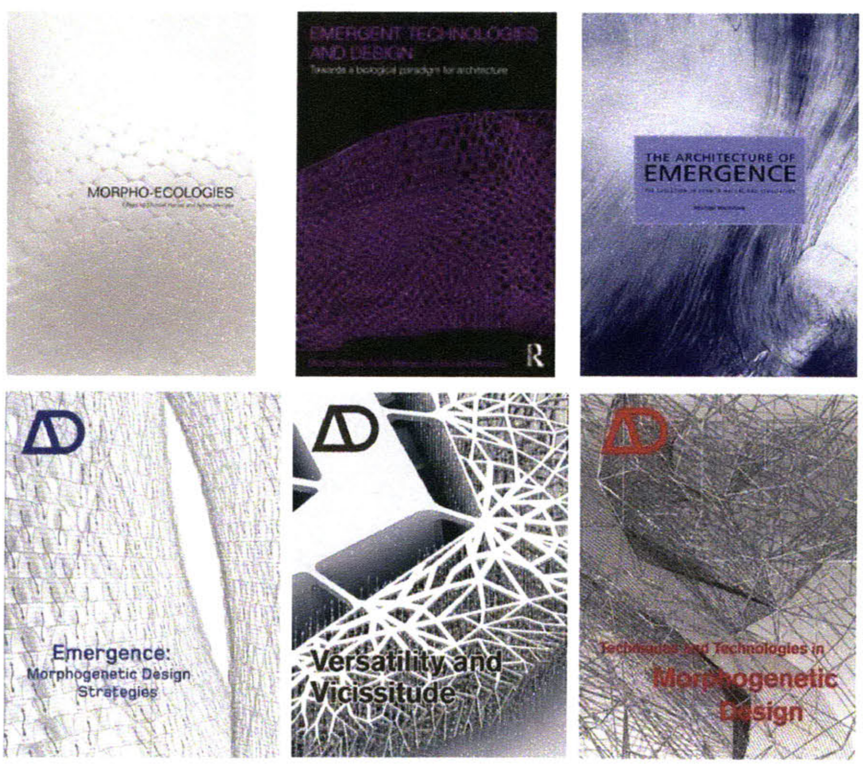


Figure 3.15

2004 - Andrew Kudless/ Matsys

In Andrew Kudless's projects, form is generated through the corollary of material behaviors and fabrication processes. Naming his practice Material Systems (Matsys), Kudless focuses on the integration between form, growth and behavior, the intrinsic nature of all living and non-living entities. His research explores the relationship among architecture, engineering, biology, and computation. The projects, including *Manifold (2004), C_Wall (2006)and P_Wall (2006)* investigate cellular aggregate structures, Voronoi algorithm and honeycomb system. He utilizes complex geometry, digital fabrication, and procedural techniques such as scripting for translation and materialization of information (Figure 3.16, 3.17, 3.18). [33] [34] [35]

Figure 3.16 Manifold

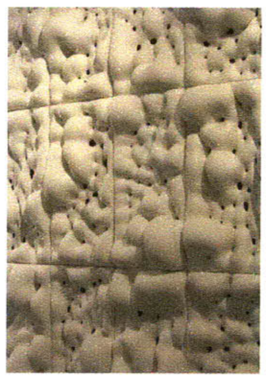


Figure 3.17 P_Wall

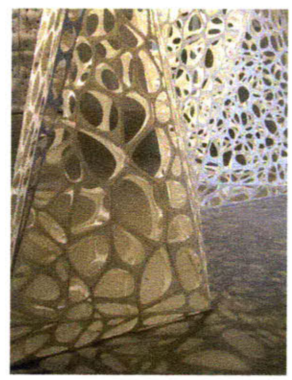


Figure 3.18 C_Wall

2006 - Chris Bosse

The German architect, Chris Bosse, creates architectural spaces, using computational methods for the study of organic structures. For *Entry Paradise Pavilion* project (2006), he investigates the form and structure of microorganisms with computer simulation. He uses a form-optimization technique rather than explicitly designing the form, a process similar to what takes place in natural organisms such as organic cells, mineral crystals and soap bubbles. The flexible material that has been used for the fabrication makes designing based on gravity, tension and growth forces possible. In his other notable project, *Digital Origami (2007),* Bosse designs a particular module to generate architectural space. Repeating the module, he explores the assumption that intelligence of the smallest unit dictates the order of overall system. As his concept source, he imitates the ecosystems such as reefs in which individual components interact in symbiosis, in order to create their environment. [36] [37] (Figure 3.19, 3.20)

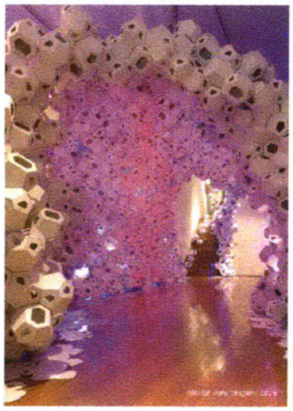


Figure 3.19 Digital Origami

Figure 3.20 Entry Paradise Pavilion

2008 - Neri Oxman/ Materialecology

Neri Oxman's material architecture projects are based on biological inspiration and interaction with their environment. She believes "The biological world is displacing the machine as a general model of design." Through her designed objects: *Construction in Vivo (2008), Cartesian Wax (2008), Monocoque (2008)*, she strives to imitate natural systems and their qualities such as multiple functionalities of living tissue and load bearing natural vascular structures. Creating special material condition for light transmission and structural support, she uses fabrication techniques and machineries such as CNC machines, lay-up technologies and single and multi-material 3D printing, engaging materials such as flexible and rigid resin, wood and melted glass. She envisions materials and structures that can perform different levels of structural stability within a single material, alter their degree of transparency for different interior light conditions, ventilate through the embedded pores in surface, and ideally supply themselves with energy (Figures 3.21, 3.22). [38] [39] [40] [41]

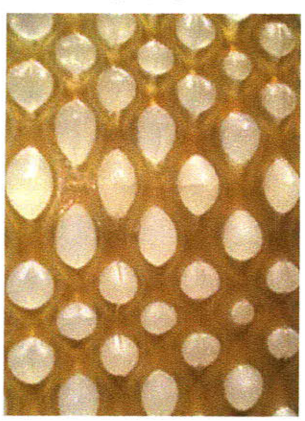


Figure 3.21. Cartesian Wax

Figure 3.22. Monocoque

2008 - Jenny Sabin and Peter Lloyd Jones/ LabStudio

LabStudio has been created through the collaboration between the architect, Jenny Sabin and molecular biologist, Peter Lloyd Jones. Their work not only investigates the ecological and generative design in architecture, but also develops new methods for observation and measuring of dynamic living systems. They engage interdisciplinary knowledge from diverse fields such as architecture, mathematics, materials science and cell biology. Lab studio visualizes and materializes the analyzed abstract dynamic and biological system to be applied on both architecture and biomedical research in projects such as *Branching Morphogenesis* (2008) and *Ground Substances* (2009). [42] [43] [44] (Figure 3.23, 3.24)

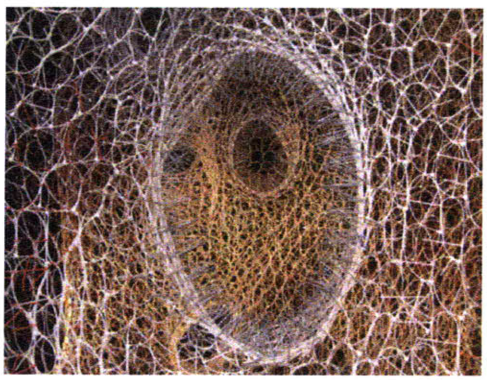


Figure3.23 Branching Morphogenesis

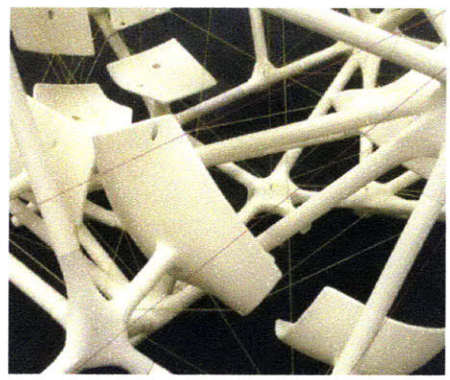
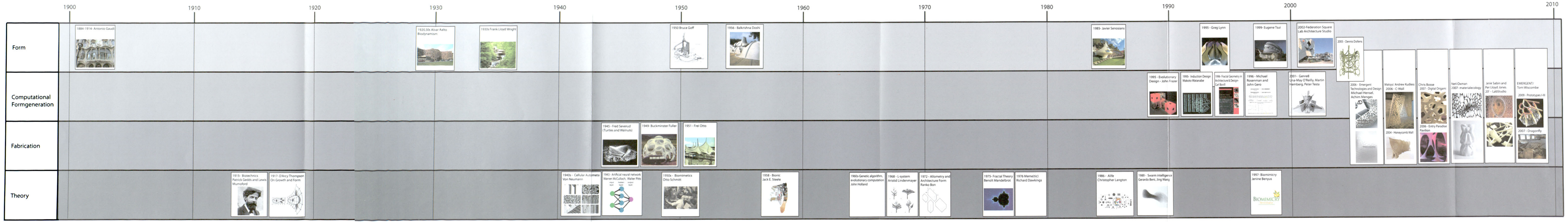


Figure 3.24 Ground Substances

3.4. Timeline of the biologically inspired design, computation and fabrication



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4. Systematic knowledge transfer

Each organism in nature inherently is a unified structure of different systems in which all of its needs for growth for conservation and reproduction are carried out within that system. In terms of production, these natural models create optimal forms based on accessible materials in their settings, the best possible use of energy, and at the same time, the maintenance of sustainable conditions in their living environment. Biological systems are like small factories where all manufacturing steps take place inside a single unit. Based on necessity and limitations, over millions of years biological systems have developed sustainable solutions, which can be adapted by researchers and designers as a source domain for new design concepts and solutions.[1] Today, researchers attempt to suggest new solutions for the development of new methods and designs in science, architecture and engineering fields by imitating nature's successful strategies. Consequently, looking into nature has hypothetical advantages for the development of integrated systems in digitally designed and fabricated architectural systems.

In the process of systematic knowledge transfer from biology to design, the important factor is the investigation into the main principles that have led to functional properties as well as form and shape of natural organisms. Scientists in fields such as material science, robotics, and computer science attempt to develop methodologies for systematic transfer of biological information to engineering and design. A scientific study for the systematic transfer of knowledge is essential because, first, the interdisciplinary essence of biologically inspired designs requires expertise in two distinct domains of biology and architecture or engineering; second, the intrinsic differences in the domains results in the divergent subjects and methods of study; and finally, natural organisms are investigated from different standpoints, as biologists are more concerned with the functional aspects of the existing biological systems while designers are keen to find new solutions out of these organisms for human needs.[2]

The systematic knowledge transfer has been investigated from with different approaches: biology-to-design and design-to-biology[3] or in other terms solution-based and problem-driven biologically inspired designs.[4] In the first method a keen observation of a natural phenomenon results in the creation of a design or solution to a design problem, while in design to biology approach, the designer searches among potential corresponding natural organisms with functional similarities, adaptable to the design challenge.[5] [6]

4.1. Biology-to-Design process

In the biology-to-design knowledge transfer method, the designer chooses a biological model with potential qualities, promising for new design ideas. By further exploration, the main features that have led to these qualities have to be determined and formulated in order to specify the range of possible design outcomes. Based on these studies on the biological models, some design proposals are made and tested. The best design idea is selected to be refined through a feedback loop with more experiments on the design model (Figure 4.1). One of the famous examples of this process is the invention of Velcro hook and fastener in 1940s by George de Mestral, which was developed, based on the precise study of the behaviors and qualities of the natural hook surface of a cocklebur under microscope.[7] (Figure 4.2)

Solution-Driven Biologically Inspired Design Process

- Step 1: Biological Solution Identification

  Designers start with a particular biological solution in mind.
- Step 2: Define the Biological Solution
- Step 3: Principle Extraction
- Step 4: Reframe the Solution

  Reframing forces designers to think in terms of how humans view the usefulness of the biological function being achieved.
- Step 5: Problem Search

  Whereas search in the biological domain includes search through some finite space of biological solutions, problem search may include defining entirely new problems.
- Step 6: Problem Definition
- Step 7: Principle Application

Figure 4.1 The procedure for Biology-to-Design Biomimicry (Helms 2008)

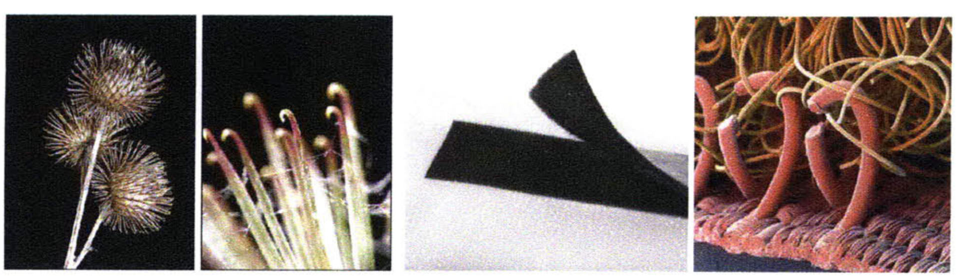

Figure 4.2 Right: Burdock flowers and Left: Velcro – Close up view of the hooks (Johnston), (Velcro)

4.2. Design-to-Biology process

In the design-to-biology cross-domain knowledge transfer method, the designers search for natural models with potential solutions for their specific design problem.

Among different proposed systematic strategies for this process, the biomimicry design spiral method, proposed by Biomimicry Institute, has been selected as the main method for this research[8] (Figure 4.3). The design spiral method focuses on the reiterative essence of the process and consists of six stages. (Figure 4.4)

First step, *identification*, is the careful exploration of the design problem and development of a summary that presents the core specifications and needs of the project. In this step, specifications of the design environment have to be considered, as they are necessary factors for the better understanding of the design needs. In the second step, *interpretation*, the defined criteria will be translated into the biological terms by inquiring about the analogous functions in nature. Questions such as 'How does nature do this function' may successfully lead to the next step of the process that is the search for the corresponding biological systems. The third step or *discovery* searches for the best models and strategies in nature, which may have corresponding solutions for the design needs. It is beneficial to consider both literal and metaphorical analogies in this exploration. Especially biologists and biomimicry specialists, because of their deep understanding of biological behaviors, can suggest natural organisms with the most successful strategies. Following this process, the underlying principles of the natural organism should be extracted. Here, classification of extracted principles may help to select the most repeated and successful design strategy. The *abstraction* of the design principles of the selected natural model is the main procedure in the forth step of the design-to-biology method. Fifth, the last phase, *emulation,* is the development of the design solutions for the project, based on the imitation of the extracted and abstracted principles of the selected biological model. This imitation can be applied to the design problem in two different levels: mimicking form and mimicking function. Finally, the derived design concepts should be *evaluated* in comparison to the natural principles. This evaluation may lead to new questions and inquiries for new a search. The whole process can be improved through a feedback loop by further exploration and application of the new lessons.

Problem-Driven Biologically Inspired Design

- Step1: Problem Definition
- Step 2: Reframe the Problem
- Step 3: Biological Solution Search
- Step 4: Define the Biological Solution
- Step 5: Principle Extraction
- Step 6: Principle Application

Figure 3.3 The procedure for Design-to-Biology Biomimicry (Helms 2008)

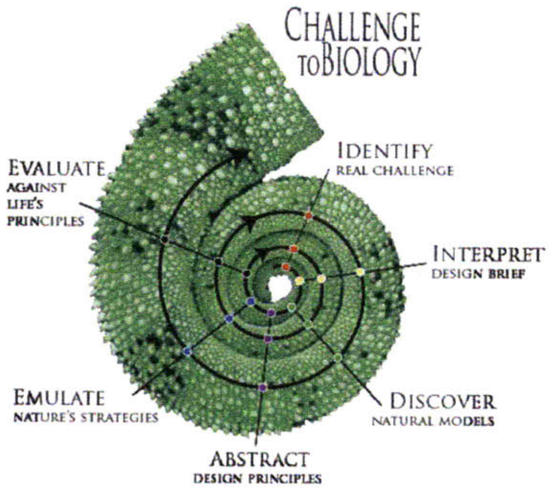

Figure 4.4 The Challenge to Biology Design Spiral (Biomimicry Institute)

Notes

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5. Recommendations for systematic knowledge transfer from biology to digital design and fabrication

5.2. Guidelines for new solutions

Learning from ubiquitous versus specific biological principles

In terms of identifying new solutions for integrated design and fabrication systems, there are some issues in the design-to-biology process that should be addressed. The main challenges to finding new solutions relate to the identification of suitable biological models and the extraction of the main principles from them. Hypothetically this identification of the corresponding models for a design problem can be approached from two different standpoints: mimicking the characteristics of a specific natural phenomenon versus learning from ubiquitous principles of natural organisms.

The first method to identify biological models, *learning from specific characteristics*, offers novel ideas for designers by revealing hidden aspects of physical, chemical and mechanical properties that are not common in our surroundings. These features inspire designers, engineers and scientists to bring new ideas to their projects and fields of study. For instance, by the study of the Morpho butterflies' wings, new colors have been created with no use of pigments or dyes.[1 2] These colors consist of fibers with different thicknesses and structures, inspired by the scales on the Morpho butterflies' wings. They refract light in different directions, presenting vibrant and lively colors, as opposed to color pigments (Figure 5.1). However, this method typically results in the development of products, tools and techniques used by scientists in such fields as material science and mechanical engineering, rather than proposes solutions for the development of broad theoretical systems. Other examples in this category are the invention of Velcro hook-and-loop fasteners inspired by Burdock. [3]

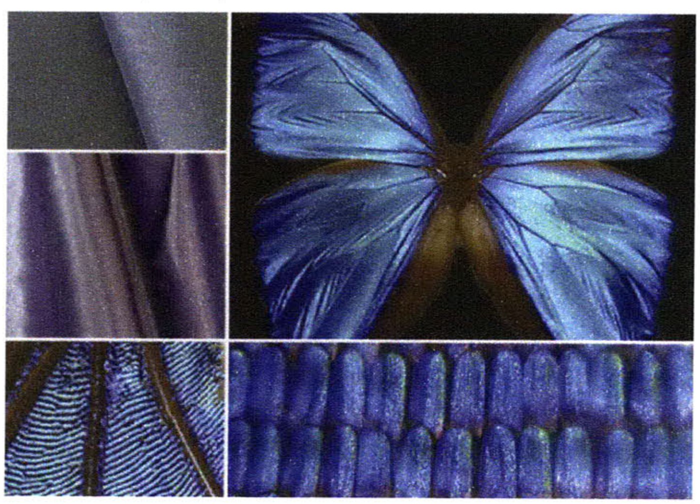

Figure 5.1. Wings of Morpho butterflies

Conversely, in the second approach, *ubiquitous principles in natural organisms,* proposes new solutions for the development of methods, processes and systems in engineering and computation. One of the best examples in this category is the evolutionary computing and genetic algorithm initiated by John Holland in the 1960s, which inspired by natural evolution. [4] This computation method is based on certain characteristics of heredity and evolution, which seem to be nearly universal. Consequently, such biologically inspired computational and engineering methods often have a broad effect on the development of many problem-solving tools and techniques in design and engineering.

These two approaches are not only different in the scope of their effect but also in the identification and principle extraction of these biological phenomena. In the first approach, which learns from specific natural phenomenon, the biological models are best investigated by biology experts with a keen eye for outstanding the functions and behaviors of natural organisms. A close collaboration and mutual understanding among these biologists and designers is the essential key for the initiation and progress of any bio-inspired projects in this approach. Some groups and organizations such as the Biomimicry Institute, Bionik Group at TU Berlin and the Smithsonian Institution provide researchers and designers with biological models corresponding to their design problems and the description of their special behaviors. After becoming acquainted with these behaviors, researchers study and analyze these biological models in more detail to comprehend and extract the rules behind the functioning systems. In contrast, the second method learns from pervasive characteristics and models in natural organisms such as genetic systems, neural networks or branching spread and distribution in plants, animals and other natural phenomenon. The identification of these models often occurs by correlating the desired behaviors of the intended design model with the surrounding natural models. However, in this case because of the associative relationship, rather than direct imitation, extraction of the corresponding principles is highly contingent on the analogy method.

Principle filtering based on the target domain

Identifying biological models with potential solutions for design problems in the previous section, the corresponding principles to the requirements of the problem should be extracted. However, deriving the relevant principles from the complex system of natural organisms is a complicated process. This is because of the correlation among the subsystems of these organisms, resulting in a principle extraction process open to a number of different interpretations. In addition, much of the relevant technical information and description in biology textbooks may be redundant. Considering a plant leaf as an example, many methods and techniques have been derived from botanical studies on the different aspects of this single biological model (Figure 5.2). The developed artifacts and systems have been inspired by both ubiquitous principles among different types of leaves as well as principles specific to certain type of leaves. From the former approach, the L-system computational algorithm, inspired by the branching system of leaves, and the Voronoi algorithm, inspired by division of cells, can be mentioned. On the other hand, the development of self-cleaning fabrics and colors, inspired by lotus leaves or the development of deployable membranes mimicking hornbeam leaves [5] are good instances of the latter approach, learning from specific principles. Ultimately, it can be concluded that the *principle filtering* and *simplification* of the source domain is conducted based on the requirements and capabilities of the target domain.

Winston clearly describes the issue of principle filtering in his book, *Artificial Intelligence,* in the section on "Learning by Training Neural Nets." He notes:

> A vast literature explains what is known about how real neurons work from every conceivable perspective. Many books and papers explain neurons from cellular perspective, diving deeply into membrane potentials and ion pumps. Others deal with neurotransmitters and the details of the activity at and near neuron synapses. Still others concentrate on how neurons are connected, tracing the paths taken by neurons as they process information and carry messages from one place to another. And still others exploit ideas from contemporary engineering, drawing inspiration from subjects as diverse as transmission lines and frequency modulation.
>
> Given this vast literature, the tendency of most people who try to understand and duplicate neural-net function has been to concentrate on only a few prominent characteristics of neurons. [6]

Later Winston explains how natural concepts were mimicked in *feed-forward neural nets* and how concepts from synapses, dendrites, axons and cell bodies were translated to Simulated Neurons consisting of multipliers, adders, and thresholds. [7]

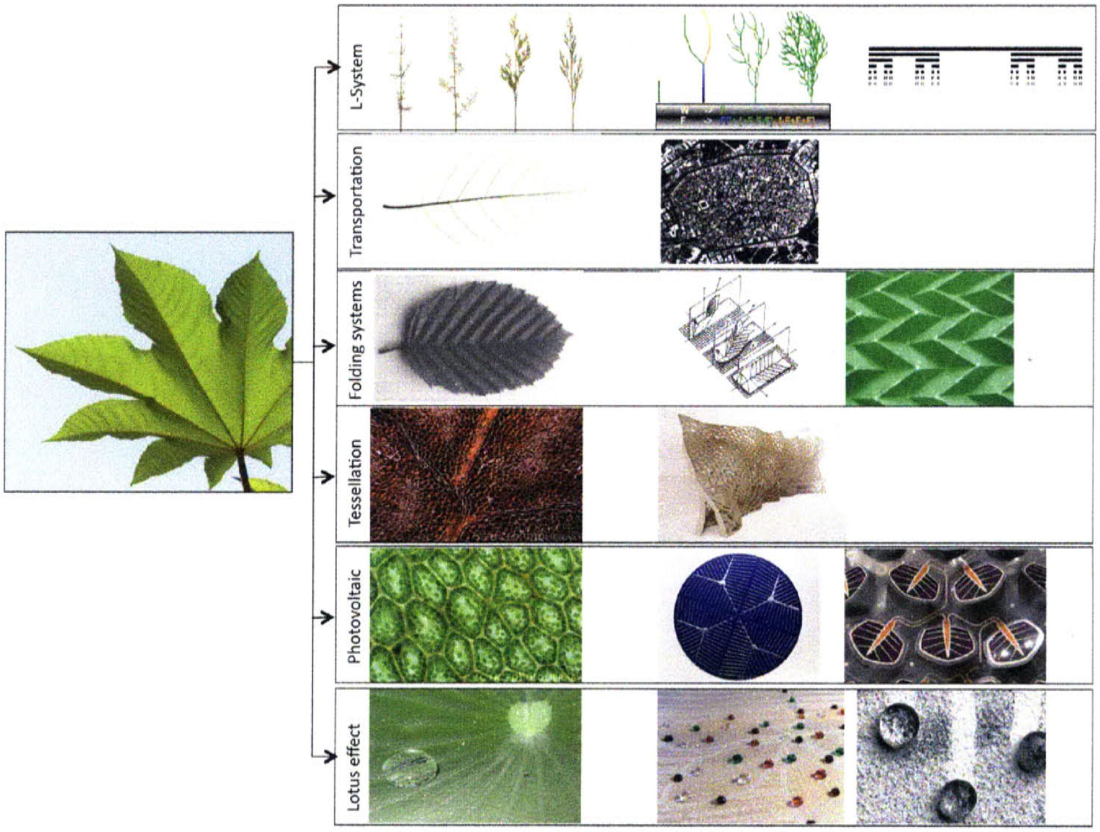

Figure 5.2. Learning from leaves in different fields of science

Independence from size and scale effects in the principle extraction process

Drawing analogies between natural organisms and design systems has been criticized based on incompatibilities in the size of the source and target domain. It is assumed that biologically inspired designs and systems are only effective at a similar scale as their natural source model, and the extracted principles would not be effective at bigger or smaller scales. Although this speculation is true in some fields of research and engineering, it is not a comprehensive rule. For instance, the principles relating to material behaviors have a direct relationship to the range of effectiveness of physical and chemical properties. For the research performed in the fields such as biologically inspired materials science or robotics, material properties such as surface cohesion and tension or thermal conductivity should be considered in the extraction and application of principles, for example the development of sticky tapes mimicking geckos' feet. [8]

However, there are many principles in natural systems that are not dependent on limitations of specific scales. A good example in this category is leaf venation, which reveals a method for optimizing length of veins and the whole surface cover. This venation pattern is similar to the distribution of streets in historic cities, which can also be applied to the design, and development of modern cities [9] (Figure 5.3). *Scale independence* is one of the important methodologies in the development of systems based on *ubiquitous principles,* systems such as genetic algorithm and swarm intelligence in computational theories.

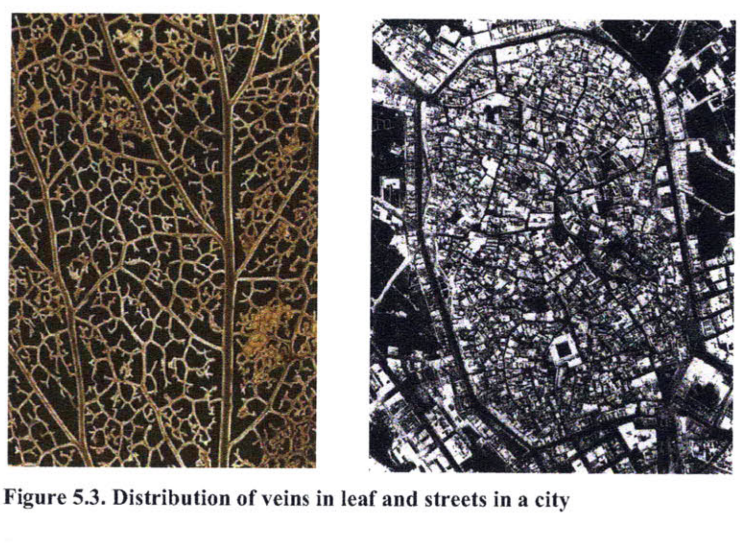

Figure 5.3. Distribution of veins in leaf and streets in a city

Learning by direct imitation of integrated entities

The identification and extraction of the main principles of a biological system usually are complicated processes. As a result, researchers and designers attempt to simplify the complexities of the system by separating the sub-systems from each other for further analysis. However, in many projects exact imitation of the whole system or body structure reveals many hidden functional aspects, which could not be conceived in advance. For example, in biologically inspired robotics, the designed robots usually look similar to the animal they are imitating such as gecko, cheetah or fish. These hidden though fundamental properties and principles of biological models reside in the interconnection of different functional elements. This is due to the mechanical behaviors of the different parts of the body on the whole system rather than to a mere formal or aesthetic imitation. Designing wall-climbing robots that are inspired by the sticky properties of the gecko's feet, the researchers have discovered the role of gecko's tail the static stability of these robots.

Consequently direct imitation on the form of biological organism is a method to avoid analysis of complex systems and sub-systems as well as to transfer the holistic knowledge of the integrated system to the target domain. This method offers the opportunity to transfer the majority of the information from the source domain's underlying principles without the need for the separate analysis of all functional sub-systems.

Notes

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6. A case study: proposing an idea for the development of integrated systems in design and fabrication

6.1. Ideas from cell level structures for the development of computational tools

This chapter presents an example of the development of a naturally inspired concept for a functionally integrated digital design and fabrication method. Utilizing the design-to-biology method, as a systematic knowledge transfer process, the first step is to clearly define the design problem. In this example, the project proposes a design system for a self-standing wall panel to be constructed with digital fabrication technologies. In the following step, the requirements of the design are defined. The essential requested functional qualities of this wall system include self-stabile structure, transparency/opacity, thermal insulation and water resistance. Based on these requirements, the most suitable biological model that corresponds to the design factors is investigated.

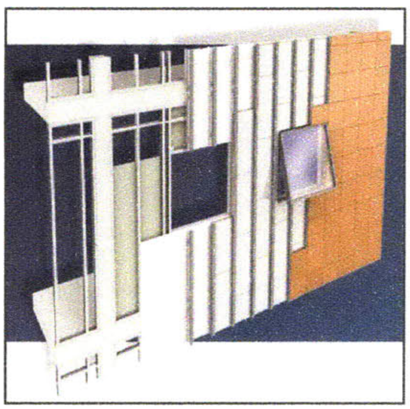


Figure 6.1. A traditional, not integrated wall system with

In this phase the researcher explores the possible corresponding biological models with qualities that can be adapted for the development of a digitally fabricated wall panel. However, the main goal is not the design of a specific wall but rather the proposal of a new *method* for the digital design and fabrication of a wall system as an integrated whole, a method that considers fabrication and operation of the wall in the design phase. Here, a beneficial technique is to define functional keywords that can bridge the design domain and the biology field to be able to identify an integrated organism with similar functions. Some of these keywords based on the functions of the wall panel are structural stability, protection, separation transmission, and thermal control. Many biological organisms may fulfill one or more of these defined functional requirements, yet the most applicable biological model is that which has higher functional overlap with the requirements of the design problem. Many potential biological organisms can be identified from both botanical and zoological studies, organisms such as plant leaves, human skin, the wall of blood vessel, intestinal wall or even insects' wings (Figure 6.2).

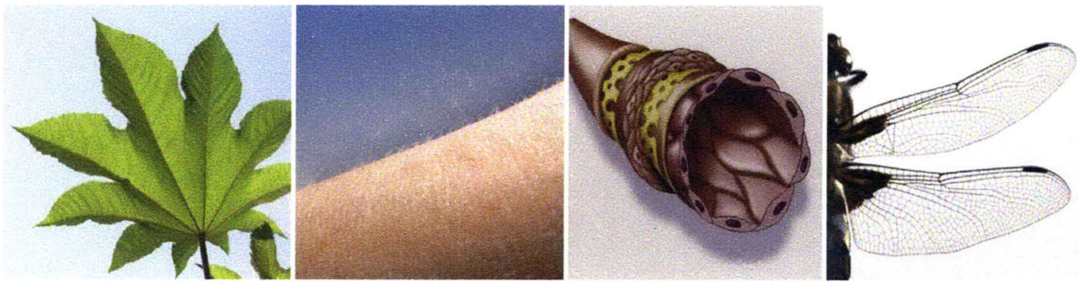


Figure 6. 2. Biological organisms as potential models for design

Identifying some potential biological models as a source of analogy, the next step is to decipher the functional behaviors and their relationship to the formation of matter in these organisms, and extract their core principles to be applied to the design problem. As mentioned, this investigation aims at developing a general *method* for an integrated digital fabrication. Considering this, the biological model selection and principle extraction is focused on the identification of *ubiquitous principles,* as described in section 5.2 – Guidelines for New Solutions. A common principle among all potential biological organisms is the cellular structure, a ubiquitous principle for the current research. Thus, a careful observation of the proposed potential models has been performed on the cellular level structure. The study of SEM (scanning electron microscope) photos of the selected organisms reveals a common trait among all these models: the layered structure of the cells. These layers of cells are stacked in functional order, each layer responsible for a specific task. *Layering* is a key principle for functional *integration* of both botanical and zoological models (Figure 6.3 and 6.4).

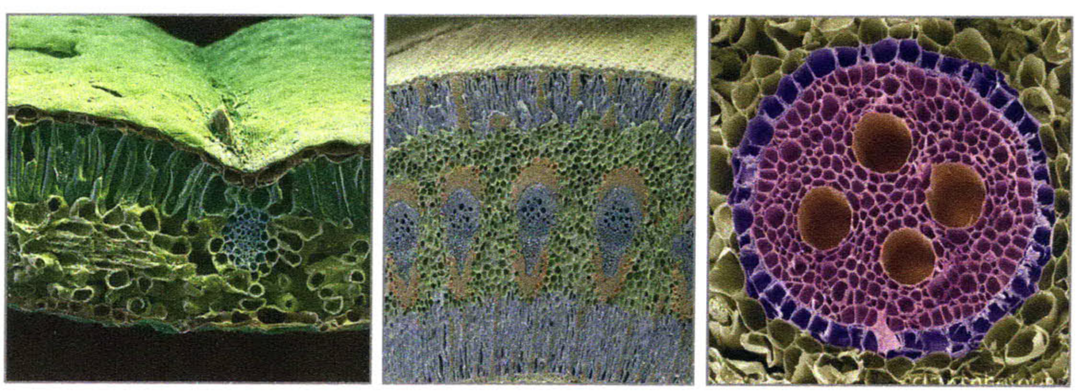


Figure 6. 3. Layered structure of plants in cellular level

Figure 6. 4. Layered structure of human organs in cellular level

6.2. Formal and developmental analysis and principle extraction from cell layering structure

Defining a framework for a new digital design and fabrication method, the layering principle can be deciphered from two different stand points, first, learning from the analysis of developed form of layers, and second, learning from developmental analysis of layers. The first method depends on the formed condition of the layers that perform specific tasks in their situated context. The second method refers to the stage in which these relatively different cells are formed and located in specific positions.

Formal analysis of developed form

By investigating the developed form of functional layers in different organs, some general facts can be extracted as base principles. These principles are the core concept in the development of a functionally integrated layered system in natural organisms: *active connection, support, and varying thickness*. The first concept, *active connection*, states that layers of specialized cells are not merely stacked on top of each other; rather there is active correlation between them. The outer layers inform the inner layers about changes in the local exterior or interior environment, changes that directly affect the functionality of the organic system. Through these active connections, the layers are able to update themselves with the received information and perform the necessary changes. In addition, the cell layers *support* each other based on their specific capabilities, such as transferring nutritious materials to the other layers or transmitting nerve signals. And finally, one of the most important principles for the integrated functionality of the cell layers is their *varying thickness*. In body organs, each layer is comprised of relatively similar cells to the adjacent layers but with few important differences, which enables them to perform different tasks. The amount of cells in each layer in a specific part of an organ is determined by the overall function of that part. For example, the cerebral cortex of the brain includes different layers of nerve cells. However, the thickness of the nerve cell layers vary according to different sections of the brain with their associated functions such as vision, hearing or muscle reaction. This is the function of each part is not determined just by a single cell type, but rather by a combination of different cells with different densities (Figures 6.5, 6.6, 6.7, 6.8).

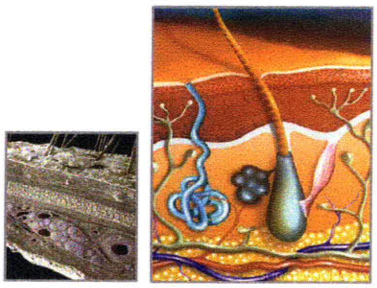


Figure 6.5. Skin

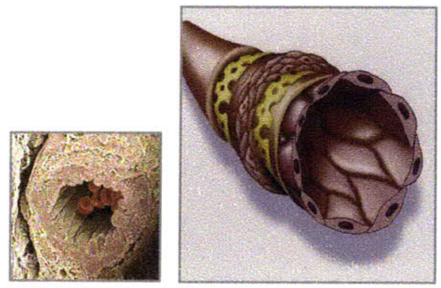


Figure 6.6. Artery

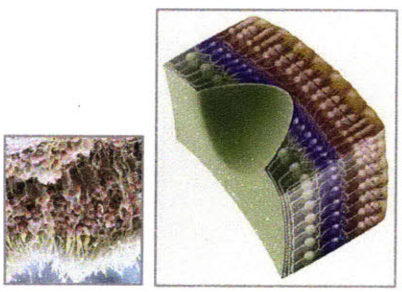


Figure 6.7. Eye

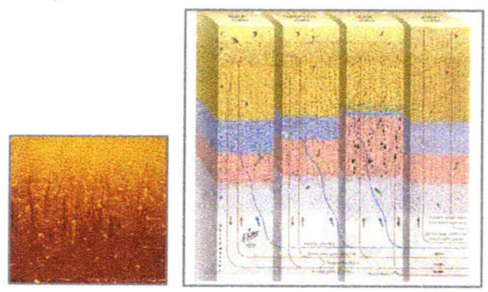


Figure 6.8. Brain

Developmental analysis

In the second approach, the analysis of the formation process of the layers can decipher the principles of the cell layering in living organisms. In the human body as well as many other natural organisms, new cells are produced by *stem cells*. Therefore, a careful study of stem cells would provide new design and fabrication methods for architecture. Given the vast and technical literature on stem cell research, the *principle filtering* based on the target domain, discussed in chapter 5, is especially beneficial to narrowing down the search for the principles drawn from the biological model and applying them to design model. This design model development could be understood in the light of its organic counterpart.

Stem cells are the biological organism's production mechanism, which are defined as: "cells that have the ability to divide for indefinite periods in culture, and to give rise to specialized cells." [1] All the tissues and organs of animals and plants are produced by their stem cells, which in a continuous process can provide the body with all its differentiated cells. [2] Stem cells are created soon after the fertilization of an organism egg. These stems cells, called embryonic stem cells, produce all the parts of the body during embryonic development. Some of these stem cells with some variations remain in the mature body of the organism after this period. They are called adult stem cells or tissue stem cells. However, these adult stem cells differ from embryonic stem cells: they cannot produce all the specialized cells of the body, but rather give birth to a group of cells from the same family.[3] For example, blood stem cells produce different types of blood cells, while the skin's stem cells or intestinal stem cells can produce different specialized cells of that part of the body.

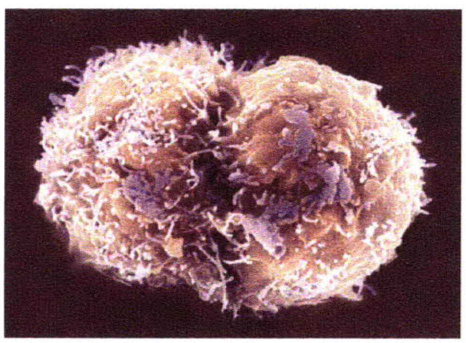


Figure 6.9 division of a stem cell

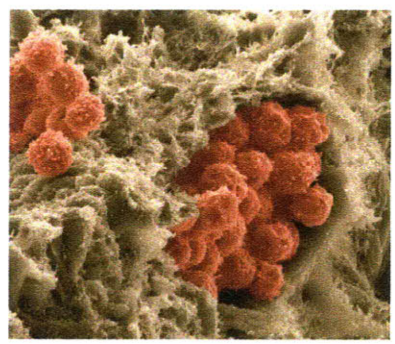


Figure 6.10 Blood stem cells

In general, stem cells have important characteristics, relevant to digital design and fabrication of a wall panel system. These characteristics can be described as: *self-renewal* as one of main properties of stem cells. These stem cells divide and reproduce themselves an indefinite number of times and over a long period. They are unspecialized, which means they do not have a special function and cannot perform any functional task. Certain factors can affect the stem cells to transform them into cells with special functions to produce cell types such as muscle, skin or bone (Figures 6.11, 6.12). These special functions are the result of the stem cells' *differentiation* process, a process in which stem cells change into *specialized* cells. The differentiation process takes place because of some internal and external signals, which the stem cell may receive. These signals consist of internal factors such as controlling genes, in addition to both physical and chemical external stimuli. External signals are usually from other stimuli such as chemical secretions and physical contacts, as well as some specific molecules called growth factors (Figure 6.13). [4]

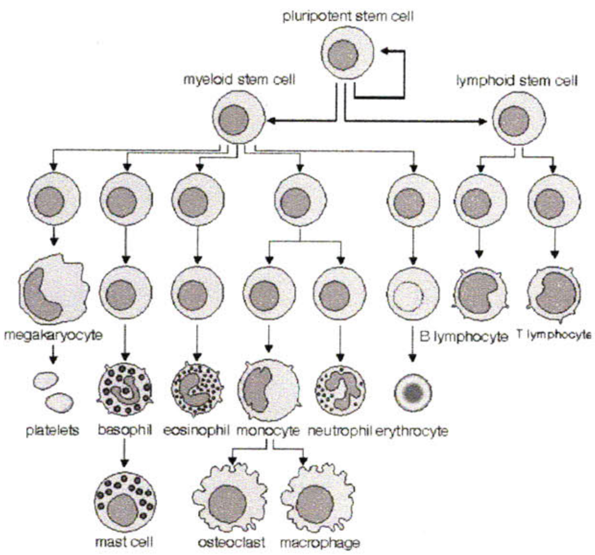


Figure 6.11 Differentiation in Stem cells

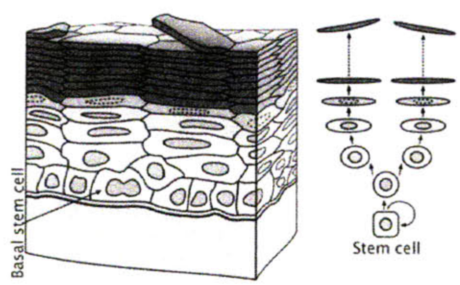


Figure 6.12 skin stem cell differentiation

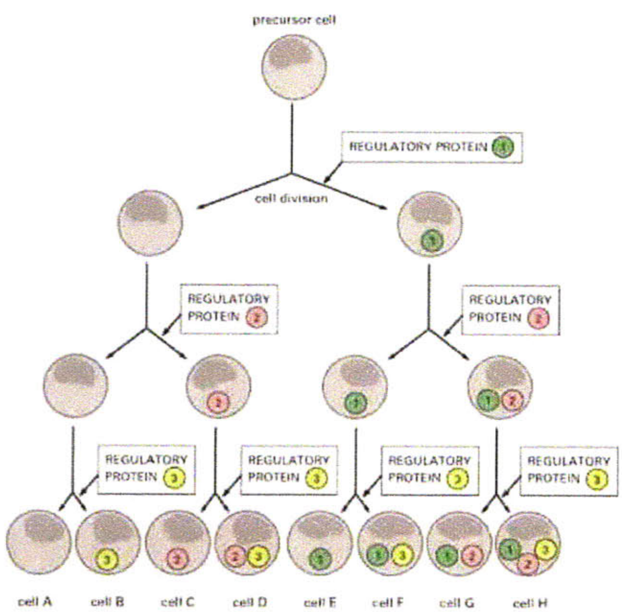


Figure 6.13 The role of regulatory proteins in stem cells' differentiation

At the next step, the principles that were extracted from the biological cell layering structures should be translated into design terms.

6.3. An algorithm for digital design and fabrication based on the extracted principles from cell layering structure

The subject of this study, as mentioned earlier in this chapter, is a method for the design of a system for digital design and fabrication of a functionally integrated self-standing wall panel. The final fabricated wall panel should satisfy certain functional criteria including structural stability, transparency/opacity, thermal insulation and water resistance, ideally with an integrated performance. The material and fabrication properties and limitations are considered in the design phase of the project, to enhance the integrity of the final prototype. The extracted principles from the biological cell layering, based on the systems of analysis, are categorized into two groups: principles derived from the fully formed layered system defining the digital fabrication criteria, and principles derived from the formation process of these layers inspiring the digital design phase.

Proposing a digital fabrication system

In the first group, principles that are extracted from the fully formed layers: *active connections* between layers, the *support* of each adjacent layers, and *varying thickness* of each layer based on the local and overall function of the system. In the design domain, these concepts describe the desired condition of the final fabricated wall panel. The analysis of the fully formed layered system suggests the use of different materials, including transparent, thermally insulated and load bearing materials, in separate layers, each of which is capable of performing different functions. Applying the extracted principles to the fabrication process of the wall panel results in a functionally integrated wall system. In this scenario, the material layers with different functions are not merely stacked up on top of each other; rather, they are fully connected and working with each other. Because of these active connections, any change in one of the layers has direct influence on the other layers, i.e., any modification or change in the thermal insulated material layer affects the conditions of the transparent and load bearing layers simultaneously. Moreover, some layers are designed to be able to *support* the other layers through a regulatory process. This special layer is equipped with data transmitter elements, forming a smart layer, which can transfer information among the layers. Finally, the most important principle is the *varying thickness* of the layers. The thickness of layers is not constant throughout the wall panel system. Rather their thickness changes in different positions based on local conditions, defined by the environment and designer.

Framing a method for the design and fabrication of a wall system with the above mentioned criteria, the current condition – qualities and limitations of digital fabrication machineries and their associate materials – should be considered in the design process. Fabrication of a digitally designed wall system, which is composed of various material layers with different functionalities, is possible with both subtractive and additive manufacturing machines. However, each group of machines has its own strengths as well as limitations. The new additive machines such as the Connex500 multi-material 3D printer [5], offer fabrication with highly integrated materials. These types of machine can print multiple modeling materials at the same time. The fabricated models with multi-material 3D printers are composed of multiple materials with different mechanical or physical properties, which are printed simultaneously, materials ranging from stiff to soft and opaque to transparent. Users can also print composite materials on the fly. The complete connection of different materials in this system results in the production of fully integrated prototypes in which all the layers act and react together in the system. However, the current condition of this technology has its own limitations, which makes it far from real architectural construction and rather more suitable for fabrication of scaled models. The first major limitation is the dimension of the fabricated prototype with this machine, which cannot make models bigger than 500 x 400 x 200mm [6]. In addition, the materials that are currently being used in this system are restricted to some specific polymer and plastic substances. On the other hand, the layered wall system can also be designed for fabrication with subtractive machines such as computer numerical control machines. The advantage of CNC machines over the multi-material 3D printers is that they can work on larger materials, closer to the scale necessary for architecture construction. Also these machines can perform on different materials such as wood, plastic, metal and aluminum, which are more common in the construction process. Although the layers fabricated with this method do not have an inherent connection between different materials, which makes the integration process far less effective. As discussed, selecting any fabrication system and its associated material has its own advantages and disadvantages, which are not avoidable with the current technology.

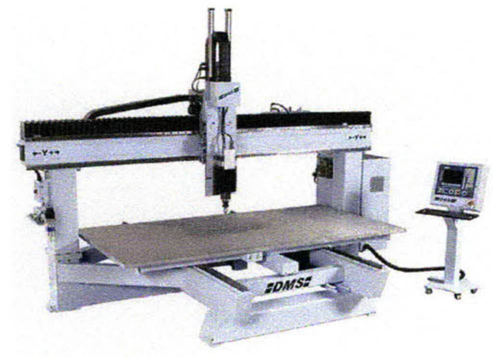


Figure 14 CNC

Figure 15 Connex500 Multi-Material 3D Printing System

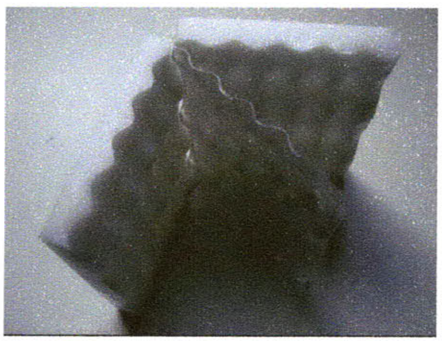


Figure 16 layer manufacturing with CNC

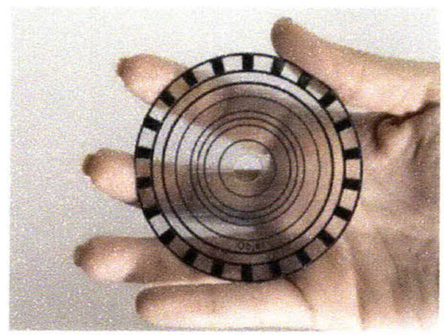


Figure 17 Integrated 3D printed materials

Proposing a digital design system

On the other hand, the principles extracted from the analysis of the stem cell specialization in the formation process of the layers in biological organisms, can inspire a digital design method, which considers the digital fabrication requirements in the design phase. The extracted principles – *self-renewal, specialization* and *differentiation* – can be incorporated in a form generation algorithm where form is generated based on the functional requirements (Figure 6.18).

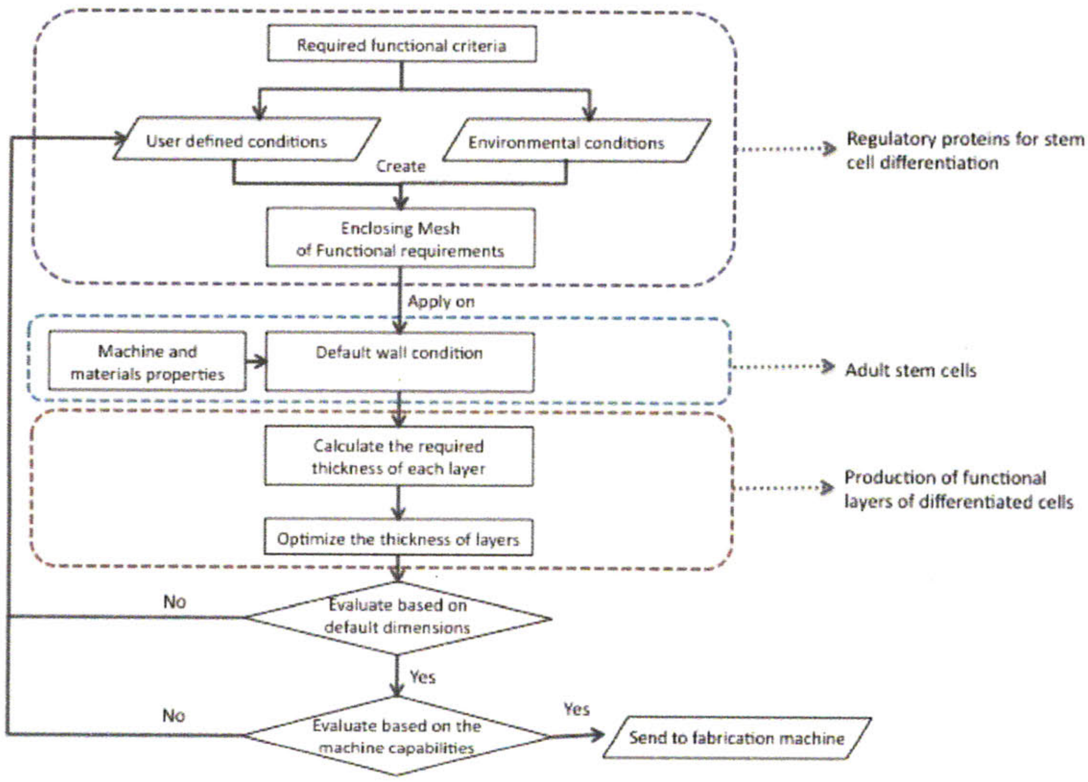


Figure 6.18. Form generation/ fabrication algorithm

In this method, a default condition for a wall panel will be created in the digital design environment. This wall is composed of small cell-like units, which represent the smallest amount of material that the selected digital fabrication machine can add or subtract. In addition, the functional requirements, both desired by the designer and imposed by the context, create a three-dimensional digital environment. The unspecialized wall will be situated in the defined digital environment. The digital environment itself is divided into smaller sections, based on the desired accuracy of the system. Each side of these blocks contains information about the desired functional conditions such as the level of visibility or the amount of thermal insulation. Situated in this informed digital environment, the wall units will be transformed into the materials necessary for the fulfillment of the functional criteria. In the next step, the differentiated cells will be arranged and optimized before being evaluated by the system requirements. Applying the functional requirements the system can be fabricated, based on the material and machinery properties embedded in the digital design system (Figures 6.19, 6.20, 6.21).

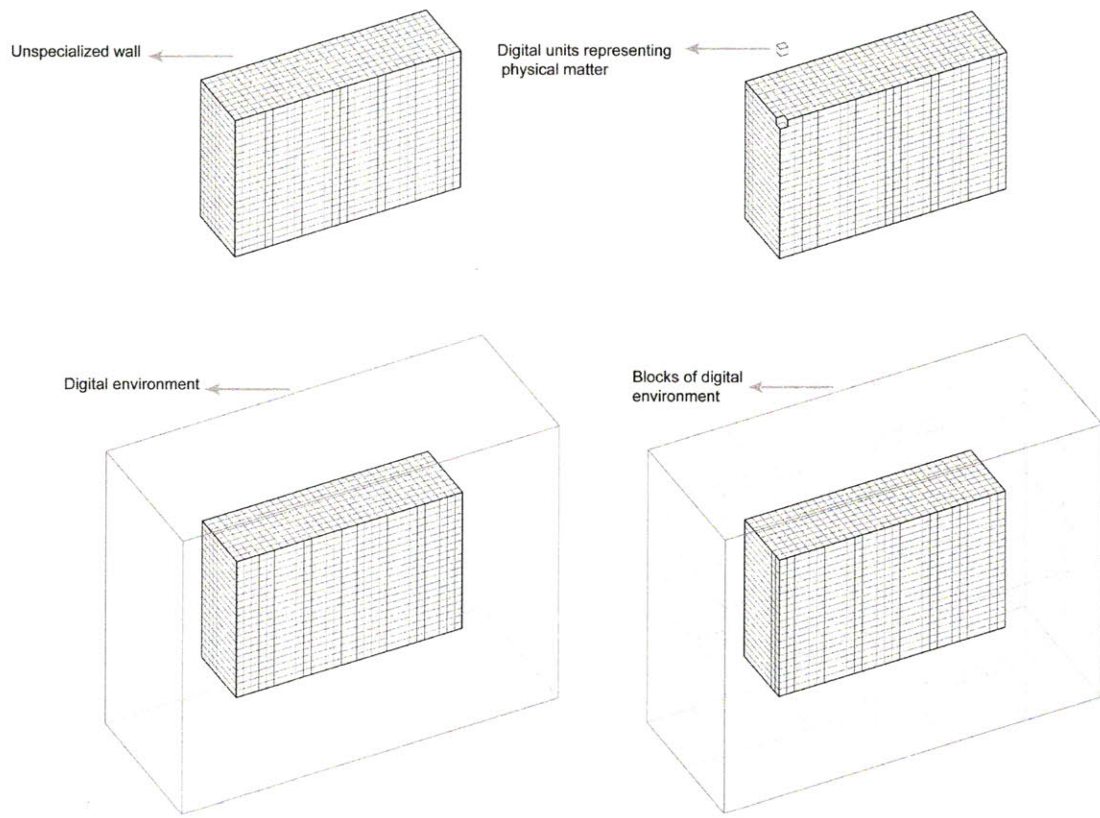
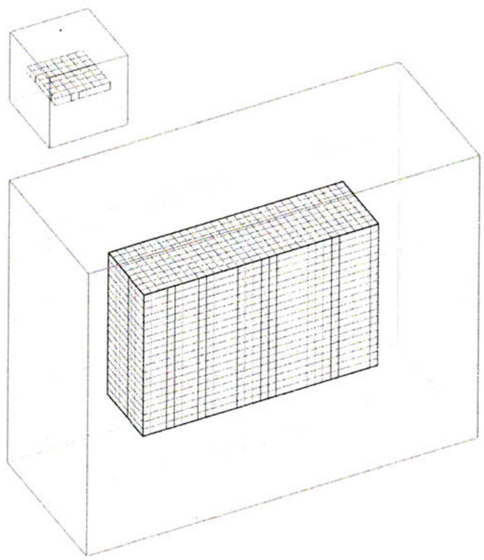
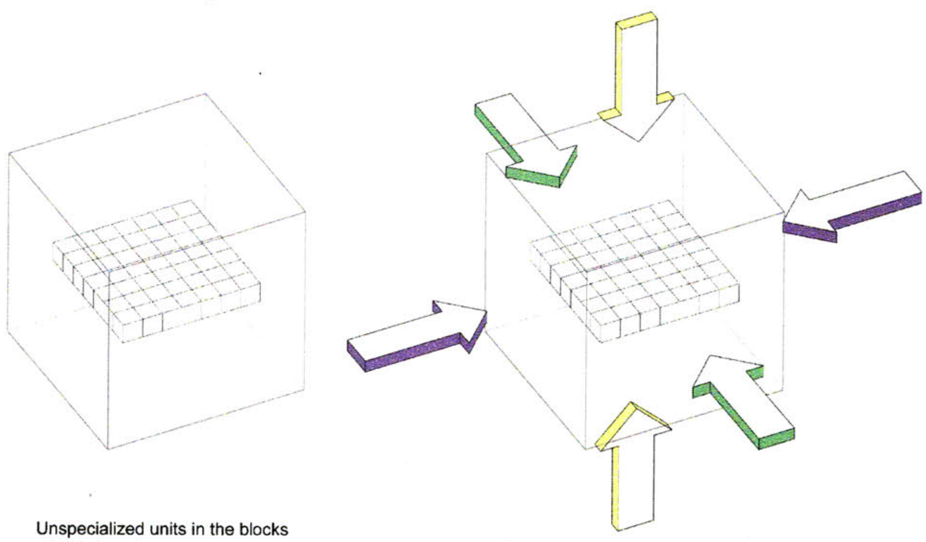


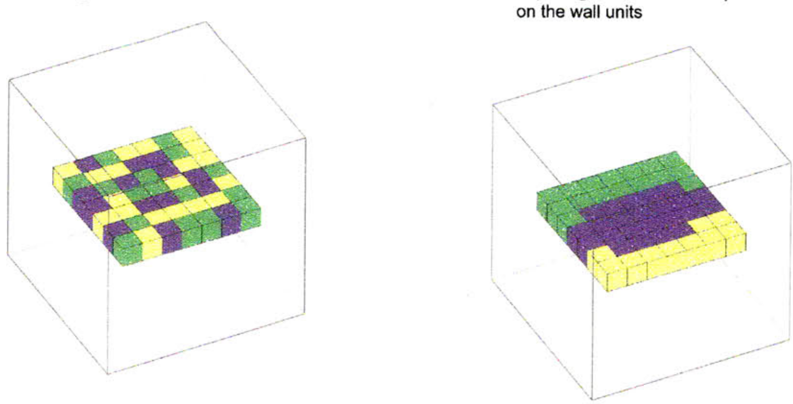
Figure 6.19





Unspecialized units in the blocks
of digital environment

Imposing the functional requirements
on the wall units



Differentiating the units

Rearrangement and optimization
of the units

Figure 6.20

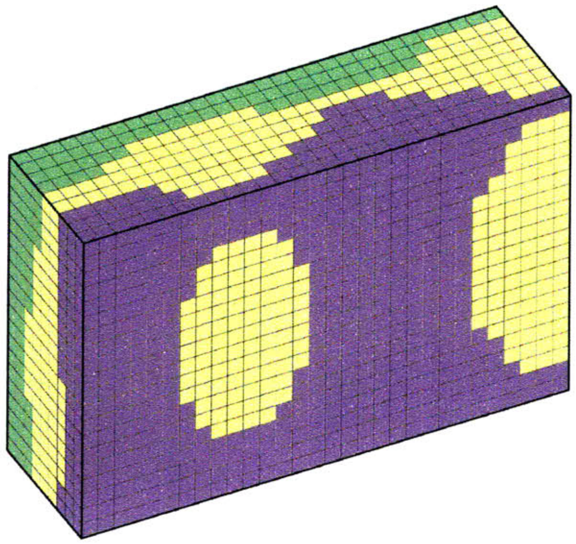


Figure 6.21

Notes

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2 . *Encyclopædia Britannica,* s.v. "stem cell," from Encyclopædia Britannica Online, http://www.britannica.com/EBchecked/topic/565211/stem-cell

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4 . Evelyn B. Kelly, *Stem Cells* (USA: Greenwood Press, 2007), 5.

5 . "Connex500™ Multi-Material 3D Printing System," *Objet Geometries Ltd. website,* http://www.objet.com/3D-Printer/Connex500/

6 . Ibid.

7. Conclusion

In the search for the development of a functionally integrated system, to be digitally designed and fabricated, this thesis aimed to draw analogy to natural organisms. Performing a background research proved that a comprehensive research on the precedents of the biologically inspired computation and digital architecture has not been developed yet. Thus this thesis found it invaluable to perform a holistic categorization on the existing biologically inspired architecture, specifically computational design and fabrication. A critical review of these precedents demonstrated that in spite of the great advances in the biologically design and fabrication methods, accompanied by novel computational theories, more research for the realization of a method for the development of an functionally integrated system is required.

Later this thesis has focused on a systematic knowledge transfer for an existing design problem. Unlike most of the precedents that the biological models have been selected intuitively, this research concentrated on a systematic investigation for the most suitable biological model, corresponding to design problem. It has been realized that although the collaboration among designers and biologist can be extremely beneficial for this investigation process, most important is that researchers themselves have an understanding of their natural environment. This understanding is a key facture not only in biological model investigation, but also in principle extraction. It is vital to be able to filter the technical biological information to come up with the principles, applicable to its own domain. Thus, this thesis has tried to propose some guidelines to present a better understanding of this design-to-biology system for designers.

Finally, it has been tried to apply this process in an example for the development of a functionally integrated wall system. The goal of this experiment has been mainly to practice and test the presented process in the development of a method for digital design and fabrication. The example documents the different stages that had been necessary for this process. Although not complete, the example presents how principle can be extracted by studying cell level structures and be applied to the development of a design and fabrication method.

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