CONSTRUCTING COMPUTATIONAL MODELS OF NATURE FOR ARCHITECTURE: A CASE ON TRANSCODING THE INTELLIGENCE OF CACTUS

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ABSTRACT

CONSTRUCTING COMPUTATIONAL MODELS OF NATURE
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The environment of knowledge exchange between computation and biology elicits a contemporary approach towards architecture. Computation, as an overarching mode of thinking, instructs the analysis, understanding and reinterpretation of the un-formal structure of natural organizations (such as systematic construct, information flow, and process through time) for architectural form generation. Consequently, the computing theory originates a mind-shift where processes, relations, and dependencies are a major concern for reconsidering and re-comprehending the environment. Besides, computation presents universal modes of thinking and tools for modeling, within which trans-disciplinary studies and knowledge interchange between distinct disciplines are flourished.

This thesis will discuss architectural form generation through interpreting computation as "transcoding" and an interface, while nature will be regarded as a "model" and a source for learning. A case study will be conducted by analyzing cactus plants and their common generative logic in the framework of computation. Consequently, the produced computational model of cactus plants will be scrutinized for probable outcomes, questioning what such a re-interpretation of natural systems may imply for architecture.

Keywords: Computational Design, Architecture Learning from Nature, Transcoding, Computational Modeling, Trans-Disciplinary Studies

ÖZ

MİMARLIK İÇİN
BİLİŞİMSEL DOĞA MODELLERİ KURGULAMAK:
KAKTÜS BİLGİSİNİN ÇAPRAZ KODLAMASI ÜZERİNE BİR ÖNERME

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Bilişim ve biyoloji alanları arasındaki bilgi paylaşım ortamı, günümüzde bir mimari yaklaşım doğurmaktadır. Bilişim, kapsayıcı ve ilişkilendirici düşünce biçimi olarak, mimari biçim üretimi için doğal düzenlemelerin/oluşumların (sistemsel kurgusu, bilgi akışı, zaman içindeki işleyişi gibi) biçim temelli olmayan özelliklerinin incelenmesi, anlaşılmasını, ve yorumlanmasını öğretmektedir. Sonuç olarak, bilişimsel kuram kapsamında süreçler, ilişkiler, ve bağlar gibi konular öne çıkmaktadır. Bilişimsel temeller ile bulunduğumuz çevreyi tekrar değerlendirme ve yeniden kavrama yolunda bir zihin değişimi yaşanmaktadır. Ayrıca, bilişimsel kuram sunduğu ortak düşünme şekilleri ve uygulama araçları ile disiplinler-arası çalışmaları ve farklı disiplinler arasındaki bilgi alışverişini mümkün kılmaktadır.

Bu tezde, bilişimin çapraz kodlama yöntemi ve arayüz olarak değerlendirilmesiyle, doğanın ise bir ‘model’ ve öğretici kaynak olarak ele alınmasıyla, mimari biçim oluşumu irdelenecektir. Önerilen yönteme örnek olarak, kaktüs bitkileri ve ortak üretken mantıkları bilişim çerçevesinde analiz edilecek ve araştırılacaktır. Sonuç olarak, kaktüs bitkilerinin elde edilen bilişimsel modelinin olası sonuçları irdelenecek; ve doğal sistemlerin böyle bir yeniden değerlendirme sürecinden geçmesinin mimarlığa getirileri sorgulanacaktır.

Anahtar Kelimeler: Bilişimsel Tasarım, Doğadan Öğrenen Mimarlık, Çapraz Kodlama, Bilişimsel Modelleme, Disiplinler-üstü Çalışma

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CHAPTER 1

INTRODUCTION

Particularly after the Industrial Revolution, architecture has been going through a shift from an interest in form production towards form generation and form finding. The basic accelerator of such a progress is the intention of deriving an explicit structure of generative design (system), where the architectural product is regarded as the associative outcome of an integrated process that intakes knowledge/information from various disciplines. Within this framework, computational thinking, constructs and medium have brought forward new initiatives in architecture. The initial widespread participation of computers in architectural design was kept limited, since they were received as tools to make the drawings of the architectural end-product. However, as computers began to be accepted as an extension of mind and thinking, architecture has become concerned with the process rather than the end-product. Consequently, architecture has grown into a mode of inquiry, experimentation and continuous exploration that is in search of a system that emerges from a well-defined set of rules. In such an approach, the generative process, which comprises complex, dynamic, integrated systems, is expected to lead alternatives of outcomes and architectural solutions, which are beyond the computing capacity of human-mind. Thus, the end-product begun to be acknowledged as one of the many outcomes of a “whole” system, which includes the integration and association of numerous aspects concerning building.

The exploration for a generative system, which would define and anticipate a variety of outcomes, has become the main interest of research in disciplines other than architecture as well. For example in weather forecasting studies, the parameters, factors and determinants of weather conditions are numerous, highly complex, and interdependent. Correspondingly, the generative system for weather conditions should integrate each variable and parameter in association with another and in a holistic structure. Computational processes and algorithmic constructions can embed and depict such complexity that will lead to distinct outcomes each time a well-associated parameter is slightly changed. In this manner, as the computational model gets more well-associated, integrated, and complex; the predictions on weather conditions get more precise and more accurate.[1] Moreover, the idea and discovery of DNA, our coded heredity that exists in all living creatures, is a conclusion of such a practice, since it is accredited as the inscription of a growth process – a generative system. Besides, a new kind of science called emergence has come into sight within this search for a dynamic rule governing system that would generate complex natural and/or social phenomena. Emergence is regarded as a 'whole' system that cannot be reduced to the individual assets of its parts and components.[2] To exemplify, a totality of a flock is more than the sum of the birds.[3] Therefore, emergence can be comprehended as a complex mechanism, where the global process of becoming is conducted through the dynamic association of local rules, agents, parameters and generators.

Swarm behavior, ant colonies, growth of cities, economy and such multifaceted phenomena have been explained and modeled within the scope of emergence, through defining a rule set that will generate the global behavior as a result of local interactions.[4] These studies, which demonstrate the complexity of life emerging from simple rules, have supported the declarations of computation. Moreover, they instructed computer science and artificial intelligence about the divergence and collective intelligence in rule-based systems. As a result of such a knowledge exchange, new study fields such as neural, cellular, evolutionary, behavioral, immune systems have been introduced to artificial intelligence.[5] In other words, re/considering and re/comprehending nature within computational principles have set forward innovations and improvements again in the computer science.

On the other hand, revisiting nature with computation has conjured up extensive impacts in architecture as well. Architecture and nature operate similarly in numerous aspects. Form, three-dimensionality, materiality, function, structural dignity, and foremost the complexity

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[1] John H. Holland. *Emergence: From Chaos to Order*. New York: Oxford, 2000.

[2] Francis Heylighen. "Self-Organization, Emergence and the Architecture of Complexity." *Proceedings of the 1st European Conference on System Science*. AFCET, Paris, 1989. P. 23. Available from: http://pespmc1.vub.ac.be/Papers/SelfArchCom.pdf Last resumed at 13.09.2011.

[3] Kevin Kelly. *Out of control : the rise of neo-biological civilization*. Reading, Mass. : Addison-Wesley, 1994. p. 10.

[4] Steven Johnson. *Emergence: The connected lives of Ants, Brains, Cities and Software.* New York: Scribner. 2004.

[5] Dario Floreano, Claudio Mattiussi. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. Cambridge, Mass: MIT Press, 2008.

and integrity of the generative system are some of the key properties shared by architectural and natural organizations. From this perspective, the process-based intelligence of natural phenomena is the primary source of learning about systems, which can instruct/conduct architectural inquiry and the form finding experimentations/explorations within the generative process it embraces.

Common to learning from nature in architecture, there has always been an enthusiasm for comprehending the governing order of natural phenomena and for *[re]*establishing/building the discovered order in architecture. Throughout history, such practice has been conducted through ascertaining 'mediating link's between nature and architecture such as proportions, mathematics, Cartesian geometry, and scale models.[6] A 'mediating link' presents its own way of thinking, understanding, correlating, structuring the generative rules and agents of an organization. In other words, the 'mediating link' determines the mode and context of *model*ing. Since Antiquity, the natural intelligence/knowledge has evolved from formal analogies towards similitude of behavior, from monadic constructs towards complex and integrated ones, from the processed towards the process. Through time, rather than the 'existence' of form, it began to be considered the integrated aspects that constitute the 'becoming' of form. Thus, as the mediatory link got more powerful and comprehensive in modeling the ordering system, the knowledge inherited from nature got more comprehensive, and dynamic. The main reason of this progress can be counted as the literacy and structural capacity of the model, which expresses, explains, and represents generative processes. Correspondingly, the 'process' gained importance as much as the product.[7]

By the advent of computational constructs and computational thinking; nature has begun to enlighten architecture about complex systems, dynamic and integrated processes through computational models. Model may lead to a multiplicity of inferences. However, the model that is referred to in this thesis can be broadly defined as "a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs."[8] Models

[6] Dalibor Veseley. "The Architectonics of Embodiment." Chapter in *Body and Building: Essays on the Changing Relation of Body and Architecture.* Edited by George Dodds and Robert Tavernor. Cambridge, Mass.: MIT Press, 2002. p. 35.

[7] Bruce Mau. *An Incomplete Manifesto for Growth*. 1998. Available from: http://umcf.umn.edu/events/past/04nov-manifesto.pdf Last resumed in 20.05.2011.

[8] Merriam Webster Online Dictionary. Available from: http://www.merriam-webster.com/

are structural representations of reality at a level of abstraction.[9] They are shaped within the constructive framework of thinking as much as the constraints/ possibilities of the literacy and medium establishing their embodiment.[10] And vice versa, a model is the manifestation of its constructive system and deriving theory. Each time we mean to understand, configure and interpret our environment within a theory, we construct models. Computational theory compels us to consider and comprehend our environment - animate and inanimate nature - another time. Thus, it urges new models, which explain the object of interest in a generative system within computational principles, operations and structures. Hence, thinking nature in forms of computational models instructs architecture how a complex and variable system can be set up from simple initials and rules.

Within the introduction and acceptance of computer as an extension of mind, the knowledge we obtain from natural phenomena and how we rebuild this knowledge for artificial systems has been reshaped. In other words, computational thinking proposes a new "mindset" that flourishes a "mindshift" in understanding the universe and its systems.[11] Computation, as an overarching theory, presents its models, patterns, modes of thinking as well as methods and mediums necessary for structuring/ constructing/ expressing them. Hence, this thesis argues that at the moment computation has become the 'mediating link' between architecture and nature, with its capacity of modeling various domains of information and potential of managing complex systems, which are comprehensive, accessible, and ductile.

In a computational resolution of a natural or artificial organization, process and information flow are well defined in a consistent and complete system, which is built up from simple initials, parameters, variables, and operations.[12] When studies on artificial intelligence turned their focus on natural phenomena after human mind; various emergent, self-organizing generative rule systems have been constructed. Cellular automata, L-systems, neural networks are pioneering models of such practice. Contemporary architecture still discovers and inquires the potentials/limitations of these ancestors. However, architecture needs to construct its own computational models of nature in order to have control on the sort of

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[9] John H. Holland. *Hidden Order: How Adaptation Builds Complexity*. Reading, MA: Helix Books, 1995.

[10] Andrea DiSessa. *Changing Minds: Computers, Learning, and Literacy.* Cambridge: MIT Press, 2001.

[11] Arzu Gönenç Sorguç. "Bilgisayarak Öğrenmek, Bilgisayarla Öğrenmek." *16. Sosyal Psikiyatri Kongresi*, Safranbolu, 4-8 July 2009.

[12] Stephan Wolfram. *The New Kind of Science.* Canada: Wolfram Media, 2002.

knowledge that will be *transcoded* into architectural design. In this respect, architecture should build comprehensive, integrated, adequately abstract, convenient and data-specific '*transcode*'s that will serve the inquiry on architectural form generation.

Within the scope of this thesis, computation is acknowledged as an overarching theory and a mode of transcoding. Frederick Jameson argues that transcoding is an equivalent function of theory, which refers to setting a shared system of language, code, structuring that would express, interpret and compare two distinct types of knowledge domain.[13] In this framework, computation is considered as a mode of transcoding that will shape the process of constructing computational models of nature for architecture. Furthermore, computation presents both the thinking mode and the medium to decode knowledge that is going to be inherited from nature, and then encode this information for the generation of architectural products. In sum, this study will aim to tackle the alterations in what architecture has been learning from nature, to redefine the association of architecture and nature through computation, and to question the role and virtue of computational models in such an association. In this context, modeling will be comprehensively examined/ questioned/ evaluated, since it will be regarded as a multidimensional architectural practice, which comprises and cultivates these research subjects.

The following chapter will include a global survey of previous and ongoing explorations on architectural design, which can be classified as the ones that are analogous to natural form, that are replicating the natural material performance based on form and geometry, that are a part of nature, and that are enthused from the natural holistic and inclusive form generative system. Thus, the evolution of approaches for translating nature to architecture will be depicted in this chapter: from the direct analogy of natural form towards the application of nature's intelligence in architecture. In Chapter 3, the theoretical background of translating/transferring the intelligence and knowledge of natural organizations into architectural design will be scrutinized in the framework of computation. The information exchange between nature and architecture will be conceptualized considering the significant position of computation in knowledge constitution through *models* and by *transcoding* nature into architecture. It shall be noted that the transcoded process and the process of transcoding are interwoven and mutually developing in the construction of computational models. In this

[13] Quoted in K. Michael Hays. "Introduction." *Architecture Theory Since 1968.* An anthology Edited by Michael Hays. Cambridge MA: The MIT Press,1998. Original quote in Frederic Jameson. *The Political Unconcious*. Ithaca: Cornell University Press. 1981. p. 40.

respect, this thesis will refer and tackle two processes at distinct scales. One is the modeled process, which signifies the becoming of the natural and artificial: the generative mechanism and system that gives rise to such an organization. The other is the modeling process, which indicates the becoming of the model: the progression of the model towards a more complex, inclusive, and associative explanation subsequent to numerous loops and branchings.

This property of dual becoming nested in the process of constructing computational models will be illustrated and analyzed extensively in Chapter 4 and 5 by a case study on *cacti*. Through this case study, the processes of *constructing*, *becoming*, and *transcoding* will be tackled and portrayed within computational principles and computational media. Cacti form will be considered as the major determinant and parameter leading the performance of water-collecting, self-shadowing, and self-air conditioning behaviors of cacti. This associated and integrated generative process of cacti form and performance will be decomposed into an algorithmic constructive system. The model of the generative mechanism will be constructed in "Rhinoceros" 3D modeling software and its scripting plug-in "Monkey" Script Editor. The constructed model will act as a generative tool, which will constitute the basis of the form finding explorations in search of an architectural form that is responding to its environmental conditions. While Chapter 4 will focus on analyzing and de-coding the generative process of cacti, Chapter 5 will centered upon en-coding a generative computational model in addition to examining and assessing the modeling process. In Chapter 6, conclusions and remarks for further studies will be declared.

CHAPTER 2

NATURE AS A SOURCE FOR LEARNING: SIMILITUDE VS. ANALOGY; PROCESSED VS. PRODUCT

Architecture has always been in communication with nature throughout the human history. Some architectural products interacted with nature environmentally, and some internalized nature in the form and generation of design. Common to both, the information existing in natural phenomena has been modeled in a particularity and structure in order to be transferred to architecture. Depending on the complexity and capability of the model, the knowledge extracted and implanted had various inferences for architecture in addition to a variety of scale, proximity, technicality, complexity, and scope.

Initial attempts to transfer/translate data from the natural world to the man-made world started with establishing metaphors, analogies, and formal similarities between the human body and building. With the intention to imitate the properties of balance, stability and symmetry of the human body, its proportional definitions have been modeled as derivations of Greek temple columns. In Renaissance, the desire for explaining forms in nature has been concluded with the implementation of the grid, which regularized the natural and thus made it possible to produce the artificial. The Grid based models are observable in the case of perspective drawings. The Renaissance man used the grid as a mediatory device to understand principles of vision, systematize reality and then draw on his canvas accurately with these principles. Later with the acceptance of a mutual relationship between form and structure, architects such as Gaudi, Buckminster Fuller, Frei Otto built scale models in order to experiment material performance under several geometries. Consequently form, geometry, and proportion gained materiality. The concept of 'similitude' and similarity in performance and behavior replaced the tradition of metaphorical analogies based on proportion.

In all these studies on nature, whenever the artist and architect tried to systematize a real entity with a medium, he modeled nature - through interpretation, a level of abstraction and a specific mode of representation. These models proved to be the common ground for discussing natural and man-made organizations; since models/modeling aim to decode and retrieve distinct domain knowledge through objective representations with a specific level of information. Over time, the contribution of nature to other disciplines evolved from metaphors and analogies towards development and management of complex systems and their behaviors. But still, the model itself has continued to be a subject of inquiry in order to achieve "*transcoding*" information/knowledge from one domain to another.

2.1. A Review of Preceding Architectural Approaches towards Nature

2.1.1. Analogy of Form: From Visual Implications to the Foundations of Parametric Setups

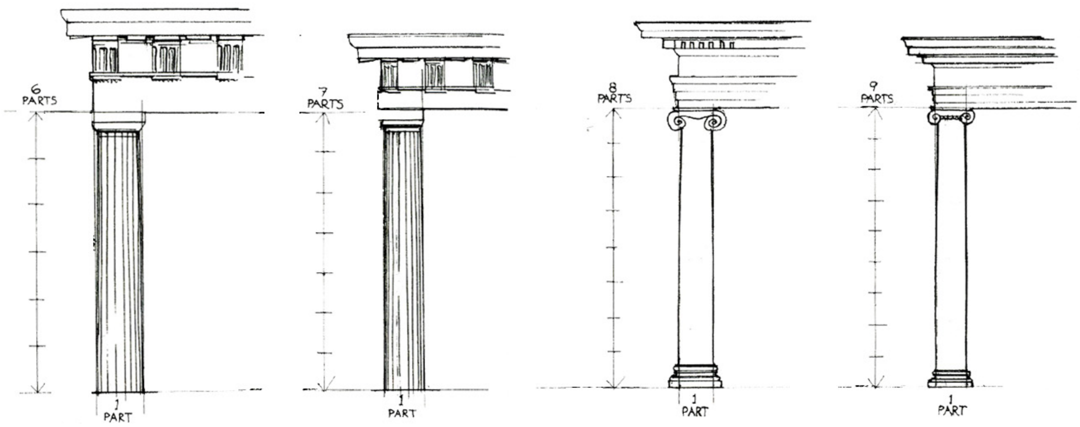

Figure 2.1 Vitruvius' illustrations on the proportional evolution of Doric and Ionian Columns, depending on the alteration of analogy object, from a man to a slender woman (from left to right).

Vitruvius. *Vitruvius: The Ten Books on Architecture.* Edited by Ingrid D. Rowland and Thomas Noble Howe. New York: Cambridge University Press, 2001. p. 214.

The beginning of the communication between nature and architecture overlaps with the moment when men began to observe his body, his environment and transfer this information to artificial constructions. First, the analogy of body and building has been flourished within ancient architecture. The 'mediating link' or 'structure' between these two distinct entities was and has been for a long period *proportion*.[14] Proportion, by Greek name 'analogia'

[14] Dalibor Veseley. "The Architectonics of Embodiment." Chapter in *Body and Building: Essays on the Changing Relation of Body and Architecture.* Edited by George Dodds and Robert Tavernor. Cambridge, Mass.: MIT Press, 2002. p. 35.

(αναλογία), means analogy, which depends on similarities and resemblances rather than numerical properties.[15]

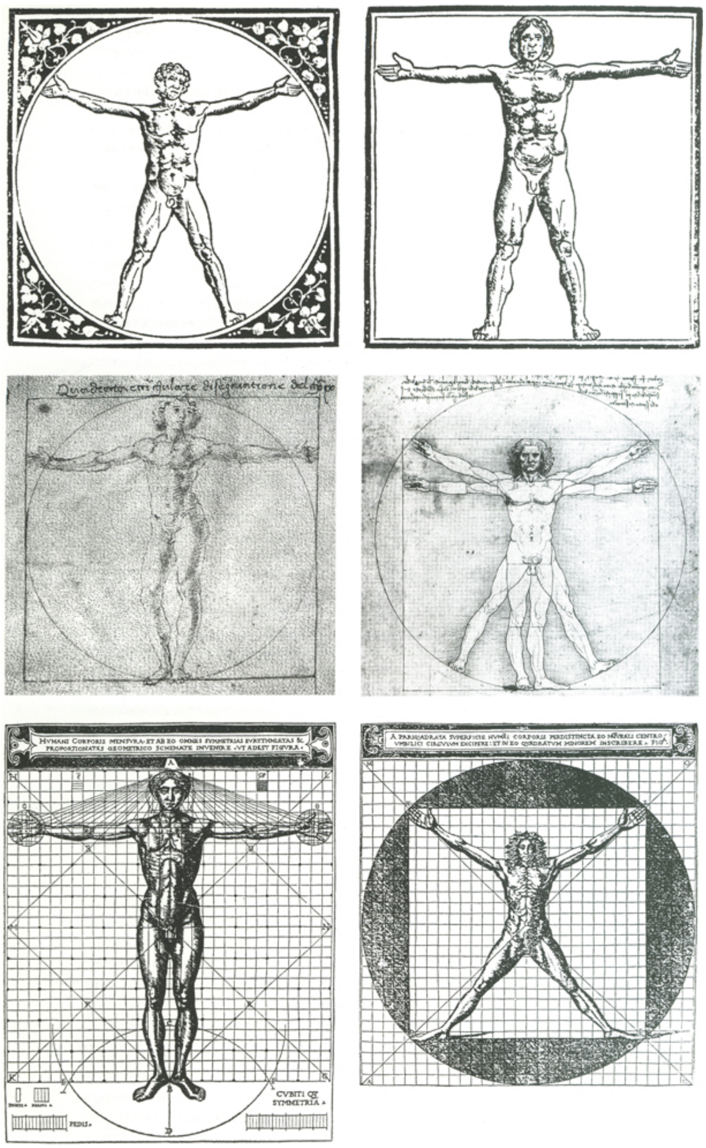

Figure 2.2 Interpretations of Renaissance artists on models of human body. (a,b) Fra Giocondo (1511), (c) Francesco di Giorgio (1480), (d) Leonardo da Vinci (1500), Cesare Cesariano (1521).

Günther Feuerstein. *Biomorphic Architecture: Human and Animal Forms in Architecture*. Stuttgart: Menges, 2002. p. 25.

Veseley mentions the obligation of a mediating link by stating: "The analogy of body and architecture would be incomprehensible without a mediating link or structure between such ontological different realities."

[15] *Ibid*. p. 37.

Roman engineer and architect Vitruvius explains in "The Ten Books on Architecture" that the proportions of Doric and ionic columns of Ancient Greek Architecture depend on the proportions of human body.[16](Figure 2.1) In this respect, the ratio of a man's footprint to his height equals to the ratio of a column's base diameter to its height. As the object of analogy alters from a man to a woman, the proportions of the column alter as well - developing towards a more slender structural element. Vitruvius, Leon Battista Alberti, Sebastiano Serlio, Andrea Palladio and more Renaissance artists explain other architectural elements of the Greek temple with proportional relations as well, such as the column base, the capital and flutes.[17] In other words, they define a 'mechanical process' based on simple fractional calculations rather than dimensions and numerical properties.[18] In this manner once the relations and parameters are set out for a type of architectural element, many more of the same type could be produced through the same generative system even if the dimensions and ratios change.

Proportional and geometrical explanations of nature and men continued to be in the spotlight of artists throughout the period of Renaissance. Proportion and mathematics stated both the theoretical common ground and method for practicing architecture, enabling control and invention.[19] Common to Antiquity and Renaissance, the body represented the nature and it was believed to include "nature's elegant way of organizing complex functions".[20] In Renaissance, the body of man is illustrated as fitting into a circle and a square.(Figure 2.2) Artists made their own interpretations while selecting the geometric shape, positioning the body, and determining the center of the geometric shape on the body. Thus, multiple geometrical constructions of human body have been acquired. In most of the illustrations, the geometry is superimposed so that the human body proportions have been modified unrealistically. The most known example is Leonardo DaVinci's representation, where two positions of a body are shown juxtaposing. Whereas the position of parted legs and raised

[16] Vitruvius. *Vitruvius: The Ten Books on Architecture.* Edited by Ingrid D. Rowland and Thomas Noble Howe. New York: Cambridge University Press, 2001. p. 214.

[17] Mario Carpo. "Drawing with Numbers: Geometry and Numeracy in Early Modern Architectural Design." *Journal of the Society of Architectural Historians*, 62(4), Dec 2003. pp. 448-469.

[18] *Ibid*. p. 451.

[19] Antoine Picon. "Architecture and Mathematics: Between Hubic and Restraint." *Mathematics of Space: Architectural Design*, Vol 81, No 4, 2011. pp. 28-35.

[20] Kate Nesbitt. "Introduction." Introduction Chapter in *Theorizing a New Agenda for Architecture: An Anthology of Architectural Theory 1965-1995.* Edited by Kate Nesbitt. New York: Princeton Architectural Press, 1996. p. 63.

arms supplies a circle, and the other position of vertical legs and straight horizontal arms fills in a square. This double representation awakens the idea that an animate feature of nature has as many geometrical constructions as its possible positions.[21] Therefore, it can be questioned if nature shall be explained through dynamic/flexible or static/inflexible relations.

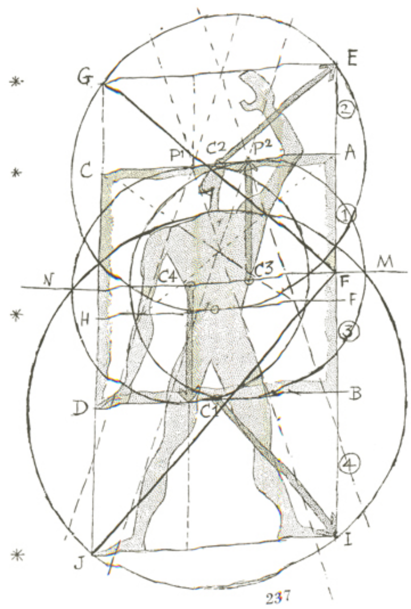

Figure 2.3 Le Corbusier's Le Modulor depicted with its geometrical derivations.
Le Corbusier. *The Modulor : A Harmonious Measure to the Human Scale, Universally Applicable to Architecture and Mechanics*. First published in 1954. Basel; Boston : Birkhèauser, 2000. p. 237.

Similarly, Le Corbusier analyzed human body through geometric elements such as squares and circles.(Figure 2.3) Nevertheless, dissimilar to the previous analogies translating the human body directly to building in proportions, Le Corbusier approached proportional properties of the human body as a basis for architectural design.[22] He analyzed man at different activities and the body at different positions; and he represented his interpretation of geometrically constructed man in the Modulor. Apart from previous attempts, he did not make abstractions of the Modulor in order to apply to the building proportions. Instead, for him Modulor was a major input for determining dimensions of building parts such as width of corridors, or height of floors.[23] With his distinctive approach, Le Corbusier broke the

[21] Günther Feuerstein. *Biomorphic Architecture: Human and Animal Forms in Architecture*. Stuttgart: Menges, 2002. p. 25.
[22] *Ibid.* p. 31.

[23] Le Corbusier. *The Modulor : A Harmonious Measure to the Human Scale, Universally Applicable to Architecture and Mechanics*, (First published in 1954) Basel; Boston : Birkhèauser, 2000.

mould of making direct proportional (and formal) analogies between body and building. He proposed a new way of knowledge interaction between nature and architecture, as he introduced dimensions and proportions of the body as a determinant parameter of the architectural design.(Figure 2.4) In this manner, he modeled his own schema of translating knowledge extracted from the human body and its contribution to the process of architectural design.

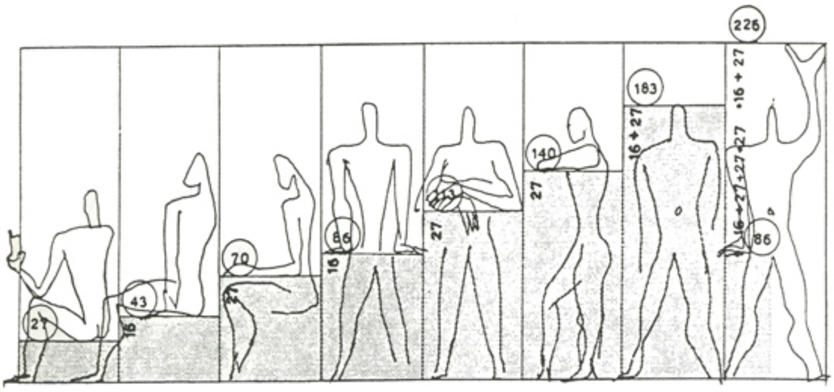

Figure 2.4 Le Corbusier's Le Modulor at different positions

Günther Feuerstein. *Biomorphic Architecture: Human and Animal Forms in Architecture*. Stuttgart: Menges, 2002. p. 30.

This ambition to find out geometric principles in the human body and natural entities is a consequence of the intention to construct analogies between nature and architecture.[24] This means that proportion and geometry has been the mediatory device that translates two distinct kinds of data into each other, acting as a melting pot where both can be described, represented and compared in terms of similarities and differences.

2.1.2. Similitude of Behavior: Towards Integrating Material, Form, Structure, and Function

Other then anthropomorphic (based on the form of human body) approaches, Leonardo da Vinci had a relentless desire for observing nature, defining a mathematical and geometrical system within it, and then deriving solutions for architecture and man-made objects. Charles Gibbs-Smith clarifies Leonardo's relentless desire of *modeling*:

> "The arithmetical and geometrical tools at Leonardo's disposal were utterly far removed from those he would have needed to fulfill the wildly optimistic hope with which he started out – the hope of completely *mapping* out and explaining any contingency in a field that still eludes such rigid statement."[25]

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[24] Günther Feuerstein. *Biomorphic Architecture: Human and Animal Forms in Architecture.* p. 21.

[25] Charles Gibbs-Smith. *The Inventions of Leonardo da Vinci*. New York : Scribner, 1978. p. 92.

Leonardo aimed to learn from nature for learning and discovering the order in natural organizations, and then to applying this knowledge and invent artificial functions.[26] Serving this goal, mathematics and geometry have been more than an explanatory tool for him; they have been the interface of his inquiries on breeding the artificial with the knowledge extracted from the natural.

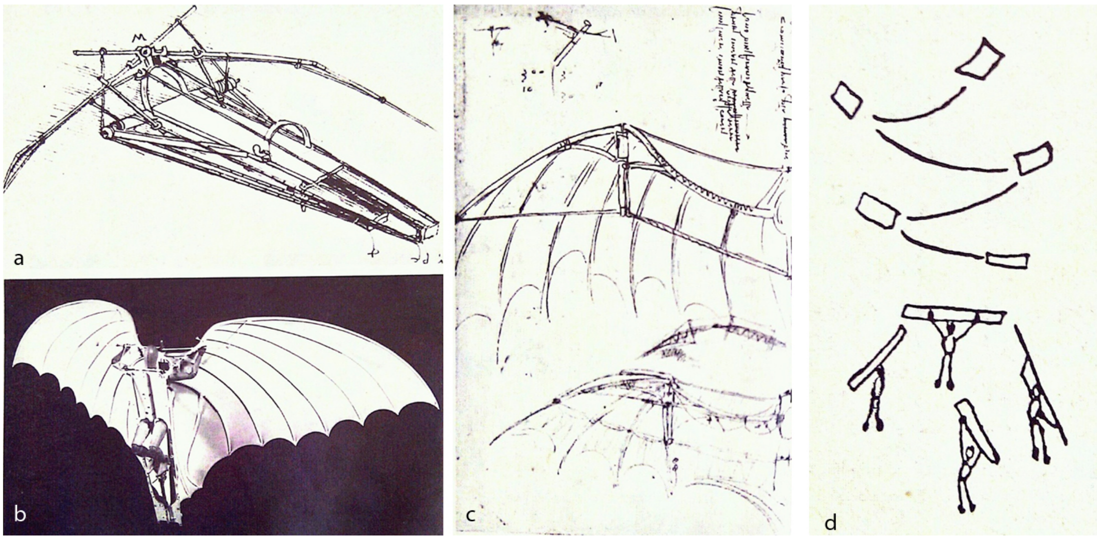

Figure 2.5 Leonardo DaVinci's investigations on flight mechanisms, evolving from flapping wings to gliding.
(a) Prone ornihopter (1486-1490), (b) model of prone ornihopter, (c) semi-ornihopter with fixed inner wings (1497-1500), (d) falling leaf glider (1510–1515)

Charles Gibbs-Smith. *The Inventions of Leonardo DaVinci*. New York:Scribner, 1978. pp. 14, 20, 21.

His studies on the flight of birds and aircraft for men (ornihopters) have started with formal and behavioral analogies; then through mathematical and geometrical constructions the studies progressed toward a correspondence in function.(Figure 2.5) His first trials of ornihopters mimicked the form and motion of the wing. These mechanisms were planned to work when a man moved his arms and legs simultaneously as he flapped the wings upwards and downwards.[27] Unfortunately, this idea did not work and he furthered his studies by developing fixed wings after he observed that the inner wing of a bird is more stable and provides lift.[28] Furthermore, at the end of his life he introduced an idea about the movement of 'gliding' as a result of his observations on the free-fall of flat surfaces. Leonardo's studies

[26] *Ibid.*
[27] *Ibid.* p. 13.

[28] *Ibid.* p. 21.

on birds, bats and movement of free-falling surfaces are the foundations of today's parachutes, planes, and miscellaneous aircraft. His researches on flying are outstanding examples for learning from nature. Notably, they established a change from making direct formal and motional analogies towards modeling integrated systems of geometry, material, natural laws (gravity and etc.), behavior, and function. This shift in the understanding of models may be called as one of the first examples of similitude.

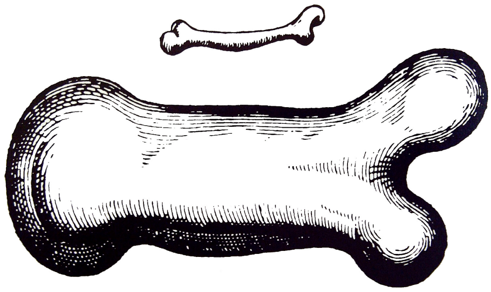

Figure 2.6 Galileo Galilei, principle of similitude is illustrated by bones that have different sizes and thus different proportional relations between parts.

Philip Steadman. *The Evolution of Designs: Biological Analogy in Architecture and Applied Arts.* First Published in 1979. New York: Routledge, 2008. p. 48

As stated by Antoine Picon, Galileo has a significant contribution in modeling discussions. Galileo's ideas went beyond simple proportion and scaling in natural analogies; he put forth the notion of 'similitude'.[29] He argued that two bones with different lengths should have different proportions of the bone length to bone diameter.(Figure 2.6) According to Galileo, the main reason for such a differentiation depends on the principle of similitude, which roughly refers to the similarity of specific behavior between two entities. In the case of bones, the change in bone proportions would sustain the similitude of structural stability and the capacity of load bearing.[30] To illustrate, the proportions of an elephant leg, a human leg, and an ant leg differ. When an ant is scaled twice its dimension, the length of its leg grows 2 times, the section of the leg grows 4 times the previous area, and the weight/volume increases to 8 times the original one.[31] Therefore, since the length, section, and volume

[29] Antoine Picon. "Architecture and Mathematics: Between Hubic and Restraint." p. 33.
Antoine Picon informs that Galileo adresses similitude in his book 'Discorsi e dimostrazioni matemetiche intorno a due nuove scienze'(Discourses and Mathematical Proofs Regarding Two New Sciences), 1638.

[30] Philip Steadman. *The Evolution of Designs: Biological Analogy in Architecture and Applied Arts*. (First Published in 1979) New York: Routledge, 2008. p. 47.

[31] Notes from the lecture of Jordi Truco. Barcelona: Universitat Internacional de Catalunya, in 2008.

increase incrementally; it is not accurate to implant the proportions of an object directly to another without interpretation, if the aim is to establish analogies of behavior. The major point of the discussion is that similitude, similarity in the structural behavior, is another aspect to consider through the process of evaluating of proportions and drawing analogies.[32] Therefore, the proportional fractions should have been modified in an analogy of a bone and a Greek column instead of a direct replicating the absolute bone proportions, since dimensions are considered as altered parameters. In this respect, Galileo has moved the inference of model beyond formal explorations, as he planted the seeds of contemporary understanding of model/modeling.

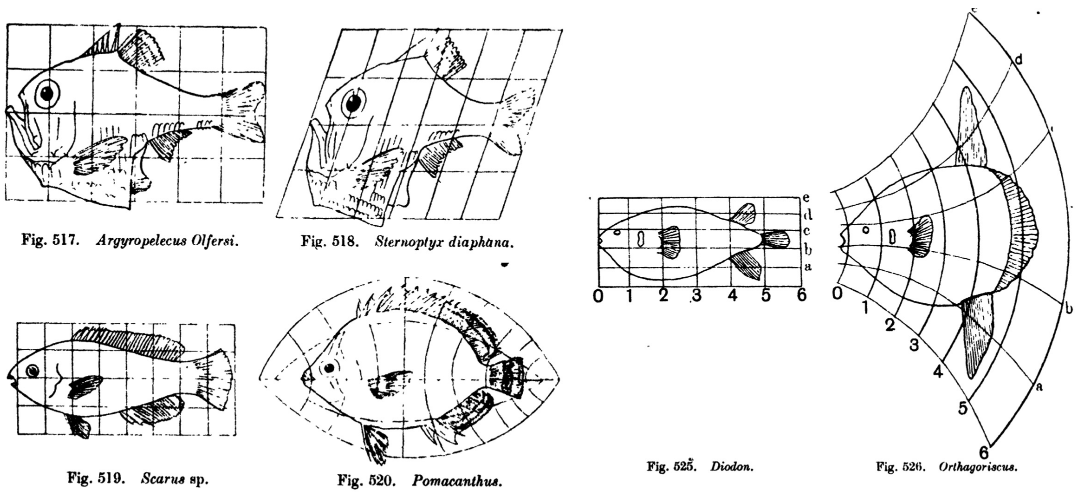

Figure 2.7 D'Arcy Thompson's morphing of fishes.

D'Arcy WentworthThompson. *On Growth and Form.* Cambridge: The University Press, 1942. pp. 1052-1064.

In the search for settling nature and natural entities on a geometrical /mathematical /proportional and yet not numerical ground, D'Arcy Thompson made numerous observations and researches on animal species in the scope of zoology. In his analyses of resembling species and their skulls, he defined all the skulls on a Cartesian grid, which would hold and mold the geometrical information on a unit-based system. Then he transformed the coordinate system; in other words, he played with the proportions of the form. As if the outline of the form is adherent to the coordinate grid lines, while the grid geometry changes, the outline is altered. Consequently, there occurs a controlled deformation of the underlying grid and thus proportions of the species' skulls. As a result of several transformations, skulls belonging to different species come to be very similar and identical after their proportions

[32] Antoine Picon. "Architecture and Mathematics: Between Hubic and Restraint." p. 33.

have altered.[33] Hence, proportion and proportional change has been a major directory for D'arcy Thompson's research, where he intended to draw analogies between two different species instead of two distinct disciplines.

Exceptionally, in his models he defined his own reference systems as a basis for comparing different species. Thompson has modified the Cartesian coordinate system via mathematical transformations. Through this method, a particular type of fish could be defined within its global geometrical properties and dependencies, and in relation to a reference system. As the reference system is rewritten and the mathematical relations are kept the same, different species are delineated from the emerging overall geometries.(Figure 2.7) For example, Thompson has mapped the form of a fish specie*(Argyropelecus Olfersi)* in reference to the Cartesian coordinate system, and then by modifying the coordinate system he examined the changes in the emerging global form and how this outcome referred to another specie of fish*(Sternoptyx diaphana)*.[34] Therefore the correlations between distinct forms in nature could be comprehended by figuring out a transformation law. Thompson explains:

> "This process of comparison, of recognizing in one form a definite permutation or deformation of another, apart altogether from a precise and adequate understanding of the original "type" or standard of comparison, lies within the immediate province of mathematics, and finds its solution in the elementary use of a certain method of the mathematician. This method is the Method of Coordinates, on which is based the Theory of Transformations."[35]

To make transformations, Thompson examines one natural form in a Cartesian coordinate system; then as an innovative attitude and as an alternative of playing with mathematical equations for defining curves, he continues with transforming the coordinate system. As if the outline of the form is stuck to the coordinate grid lines, while the grid geometry changes, the outlines are reformed. This way of representing the transformation of the coordinate system becomes a significant study in mathematics: deformation of forms by stretching without tearing called topology. In other words, with this approach Thompson goes beyond the limits of Euclidian geometry and deformation of the grid for comparing proportions came to be the determinant factor of rules, variables and parameters of the model. Thus, Thompson's approach can be interpreted as one of the first models that ascertain analog computing.[36] He takes the control on the reference system by interpreting it as a white box

[33] D'Arcy W. Thompson. *On Growth and Form* (second edition), Vol I. Cambridge: Cambridge University Press, 1959. p. 10.
[34] *Ibid*.

[35] *Ibid*. p. 1032.

[36] Lars Spuybroek. "The Structure of Vagueness," Chapter in *Performative Architecture Beyond Instrumentality*. Edited by Branko Kolarevic, Ali M. Malkawi. New York: Spon Press, 2005. p. 167.

model, where the parameters of the mathematical system/construct are explicit and adjustable. Therefore, D'Arcy Thompson builds the reference system as a parametric construct; and in this way he questions/emphasizes the adjustable and revisable aspect of a reference system.

Yet, nature's input to architecture remained in the level of analogy and mostly a formal one. On the other hand, considering similitude of behavior and its generative mechanism brings forth more integrated and comprehensive models. Distinct from similarity, similitude would lead us towards discovering fundamental common principles of distinct organizations that establish similar behavior of a specific kind.[37] Furthermore, a level of setting similitude includes the translation of these principles as the generative mechanism for architectural design and engineering. In this manner, models are conceived as aggregates of both outcome and process, intertwined. And the similitude of behavior and its generative mechanism acts as a tool for modeling where specific kind of knowledge is transfered/translated from one domain to another.

Figure 2.8 An example of Frei Otto's Soap film models and Tensile Structures.

Frei Otto, Bodo Rasch. *Finding Form: Towards an Architecture of the Minimal*. Stuttgart: Menges, 1996. p. 77.

The behavior of soap bubbles and drops of water can be considered to illustrate similitude. Both are consisted of spherical shapes as their common property. This shaping depends on

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Spuybroek brings forth the idea that Gaudi and Frei Otto's suspension models have been examples for analog computing. In this thesis, it is stated that the becoming of form under a reference system includes prior studies by D'Arcy Thompson. By questioning the reference system, he examined the alterations in the morphology of natural entities.

[37] John H. Holland. *Emergence: From Chaos to Order.* New York: Oxford, 2000. p. 6.

the fact that spherical arrangement minimizes surface tension.[38] Here shape is considered as a parameter that is effective on load distribution and stress calculations. In view of that, Frei Otto has experimented performance of soap film models in order to calculate minimal surfaces. This research guided the architectural form generation of his tensile and membrane structures.(Figure 2.8) Concordantly, regarding similitude leads to models that are interfaces for configuring which knowledge is going to be extracted and how it will be *transcoded*.

Before making further explanation about Otto's work, Gaudi and Buckminster Fuller must be mentioned with their scale model constructions as first attempts to establish similitude, Their models aimed to configure the correlation of the three-dimensional geometry and structure which exists in all natural phenomena. Gaudi has been inspired from patterns, structural stability and the economy of form belonging to natural organizations. He has observed natural organizations and realized that there is a rule governing them that relates form and structure tightly.[39] Through his observations on natural forms, he realized that in nature there does not exist regular curves but parabolic curves. Instead of a formal analogy, he built suspension models where he could experiment the emergent geometry and behavior of a material-based organization under the physical laws of gravity. As his suspension models approved, he found out that parabolic curves achieved the free flow of loads.[40] In his work on Sagrada Familia, he built up suspension models that would generate the form of the structure. When turned upside down with a mirror, these suspension models would give the most proper form of the construction that would carry the required building load and reach the intended height. In this technique, the reference system is determined by physical conditions such as the length of the chains, material weight, and laws of gravity. Hence the becoming of form under these forces and the assembly configuration are considered as crucial for the form generation of architectural products.

Therefore, the experimental scale models have been hypothesis proofs, analysis tools and design guides for Gaudi. In this manner, these scale models came to be the interface that oriented the inquiries about what the knowledge of the natural world may imply for the world of man-made. More importantly, when he designed the scale model as an interface, also he systematized the complete process of information exchange between nature and

[38] Frei Otto, Bodo Rasch. *Finding Form: Towards an Architecture of the Minimal*. Stuttgart: Menges, 1995.

[39] Daniel Giralt-Miracle. *Gaudi – La Busqueda de la Forma: Espacio, Geometria, Estructura, y Construccion*. Barcelona: Lunwerg Press, 2002.

[40] *Ibid.*

architecture. In his approach, the material models are regarded as the translation/*transcoding* media and medium, which may vary depending on the kind of knowledge that is going to be transferred. In other words, as the modeler builds the connection between knowledge, media and medium, he determines the interface – thus the modeling system.

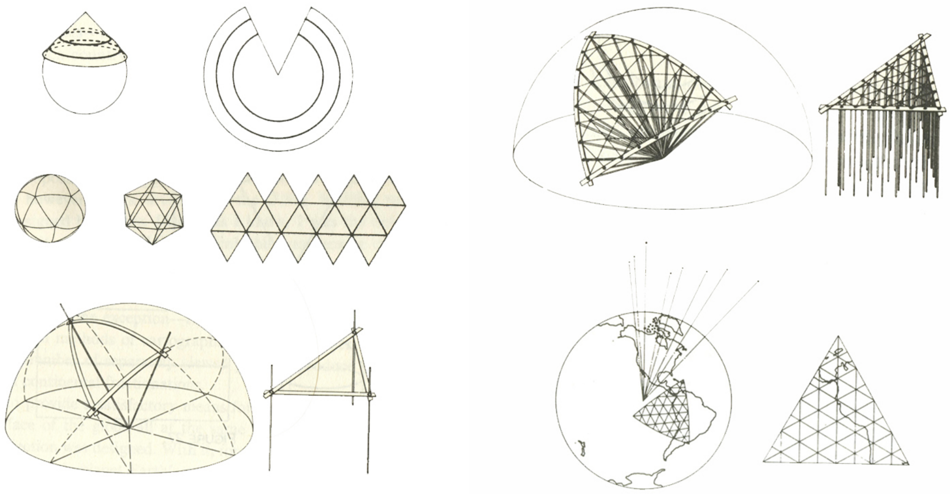

Figure 2.9 Buckminster Fuller's sketches about the development of geodesic domes.
Graphics collected from: R. Buckminster Fuller. *The Critical Path*. pp. 164, 165, 166.

Buckminster Fuller's geodesic domes are derived from the spherical form of the Earth. When a person observes a scale model of the Earth, she/he can perceive only one part of the global surface. Depending on the angle of vision and her/his distance with the model, the perceived piece of area gets smaller or wider.[41] In this respect, the scale model of the Earth triggered Fuller's geometrical discoveries about a new form of order, which would express and represent a globe.(Figure 2.9) Hence, the preceding model turned out to be the predecessor of a prospective one. Consequently, Fuller's geodesic domes are a result of learning and knowledge constitution feedback loop, where the established model is re/analyzed, re/comprehended and re/constructed.

Frei Otto followed a similar path with Gaudi, experimenting material behavior and form finding.[42](Figure 2.10) Through his observations of animate and inanimate nature, Frei Otto conceived structural stability as the association of material and geometry. He examined natural materials and forms in terms of their self-forming, self-optimizing properties in order to derive bases and methods for finding form in architecture.[43] As mentioned before, one of

[41] R. Buckminster Fuller. *Critical Path.* New York, N.Y. : St. Martin's Press, 1991.

[42] Lars Spuybroek. "The Structure of Vagueness." p. 167.

[43] Frei Otto, Bodo Rasch. *Finding Form: Towards an Architecture of the Minimal*. p. 14.

Otto's works concentrated on experiments of soap film models that would guide minimal surface calculations, which guided tensile and membrane structures. Additionally, Otto analyzed the branching structure of trees focusing on load and stress distribution where wide spans needed to be passed with little interference on the ground such as bridges, exhibition halls, and train stations.

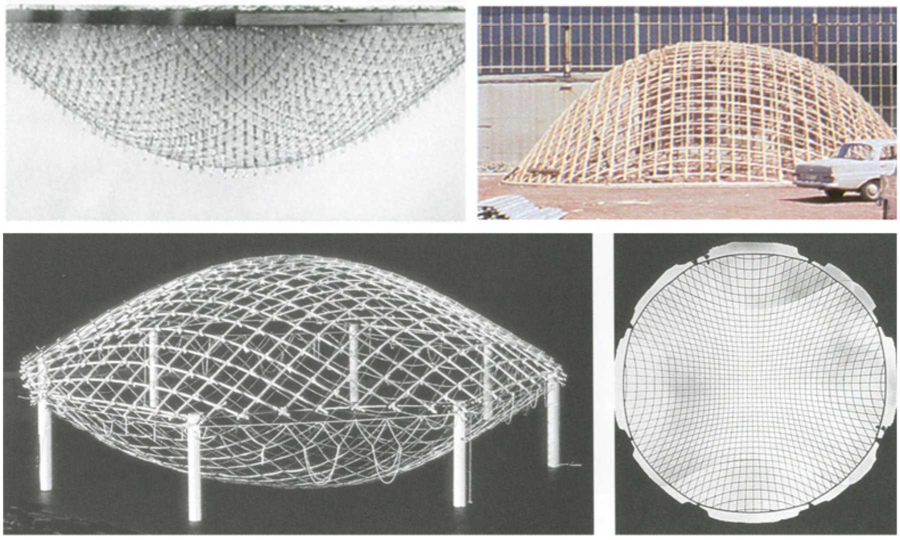

Figure 2.10 Several suspension models from Frei Otto.

Photos collected from: Frei Otto, Bodo Rasch. *Finding Form: Towards an Architecture of the Minimal*.

In all these studies on nature, whenever the artist or architect tried to systematize a real entity with a medium, he modeled nature - through interpretation, a level of abstraction and a specific mode of representation. These models proved to be the common ground for discussing natural and man-made organizations, since modeling enlightens specific information through a neutral representation that can belong to more than one type of entity. Furthermore, models can be very simple or complex depending on the accuracy and extend of the intended information. As the analogy evolves from absolute proportion towards structural stability, it can be observed that models of nature happen to be evolving towards more complex, and yet not complicated systems.

2.2. The Altered Implications of Nature for Architecture by the Introduction of Computation

2.2.1. Computation as the 'mediating link'

In the 20th century, together with the invention of computers, the idea of well-defined processes that concludes with a multiplicity of outcomes turned into a framework guide for learning from animate and inanimate nature. The rise of computation as a mode of thinking, theory, and tool structured the extracted knowledge, and thus models of natural entities. At this point, artificial intelligence as a field of study emerged with the aim of making biological intelligence and machine intelligence analogous to each other. First attempts focused on human brain and cognition. With the 'philosophical revolution' in the understanding that the human being is no longer in the center of the world,[44] the focus of interest has moved towards biological organizations, natural phenomena and processes at various scales. Correspondingly, these observations led progression about systems such as cellular automata, evolutionary algorithms, artificial immune system, neural networks, collective intelligence, and swarm behavior.[45] These systematic setups are computational models of natural organizations, some at the level of inspiration and some at the level of similitude. These artificial systems are computational models, which share the properties of natural organizations such as self-replication, self-organization, pattern recognition, adaptation, feedback mechanism, and more. Hence, the inherited knowledge through these models is the structure of generative processes, instead of merely formal or structural properties.

This shift from form-centered models towards process-centered models has reshaped the analogical approach in architecture as well. Once the generative process, constraints, rules, and system belonging to natural organizations began to be transferred to architectural

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[44] Dario Floreano, Claudio Mattiussi. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. Cambridge, Mass: MIT Press, 2008. p. xii.

Kate Nesbitt. "Introduction."

Floreano puts forth the term 'philosphical revolution' referring to the change in the perception of man as the center of the world. Also Kate Nesbitt declares that in the same period there has been a shift from humanism to modernism, and this shift has altered the anthropomorphic approaches in architecture. Nesbitt informs that Michael Graves emphasized modernism's emphasis on the 'internal language' of a building and thus its rejection of anthropomorhic representations. And Peter Eisenman states that within this change, man has been no longer the 'originating agent'.

[45] Dario Floreano, Claudio Mattiussi. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*.

knowledge, there appeared to be a deeper similitude of behavior between the natural and the artificial. For example, Otto's contemporary works and researches are centered on the concepts of pattern cognition and self-organization. He analyzes natural organizations in terms of their underlying processes and rules of occupation and territories, connection and assemblages.

According to his taxonomy, occupations include geometrical shapes and forms that act like systematic patterns. Connections, on the other hand, are the essential functions and operations of behavior that determines this geometrical configuration.[46] To exemplify occupations, a flock of birds has the property of three-dimensional occupation based on attraction, by which the birds try to maintain their proximity to each other and the birds on the boundaries press towards the center.[47] In the case of connections, the branching structure of trees, rivers or city roads can be considered as path systems, which show the properties of being useful, effective, and economical.[48] Accordingly, Frei Otto has executed an intensive research to systematize direct and minimal path networks, and analyzed the growth of occupation corresponding to the generated path. His works provide fundamental principles for understanding, configuring, forecasting the growth of cities, human settlements and their connection roads.

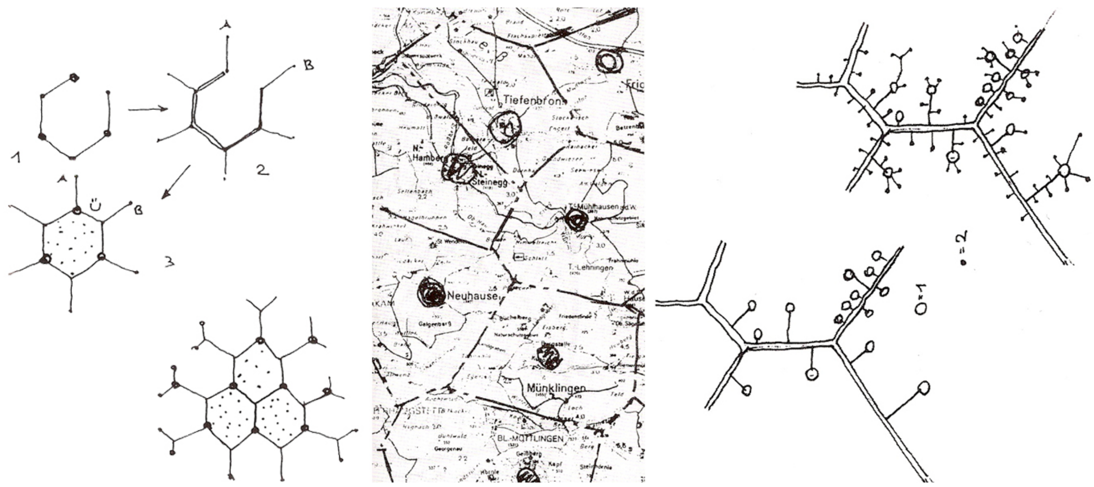

Figure 2.11 Frei Otto's studies on the processes of occupation and connection.

Graphics Collected from: Frei Otto. *Occupying and Connecting: Thoughts on Territories and Spheres of Influence with Particular Reference to Human Settlement.*

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[46] Frei Otto. *Occupying and Connecting: Thoughts on Territories and Spheres of Influence with Particular Reference to Human Settlement.* Stuttgart: Menges, 2009. p. 50.

[47] *Ibid*. p. 12.

[48] *Ibid.* p. 52.

Thus, the type of knowledge extracted from natural organizations has changed extensively in the later works of Frei Otto. Dissimilar to his previous studies on formal and structural investigations with soap films, he began to examine soap bubbles in terms of their attraction-based occupation, territory assemblage, emerging polygonal and polyhedral patterns as a result of packing, common generative rules deriving similar formations and voronoi like configurations in nature.(Figure 2.11) Therefore, the same natural entity came to be implying different types of information depending on the theoretical framework that guides the research and structures the model.

Throughout history, the change in the type of knowledge extracted from nature is mostly due to the theory, representation and thus mode of modeling. The model language has been the major determinant of the model structure and the information it can embody and transfer. In Antiquity, geometry and proportion has been the 'linking element' between nature and architecture.[49] In Renaissance, the grid was the general infrastructure that would regularize the natural and generate the artificial in a unit-based domain. Thus, models of nature have been prescribing the knowledge that the linking element could represent: geometrical, proportional, mathematical, or grid-based, in other words morphological properties.

Recently, as a consequence of the developments in information technologies, computation turns out to be the 'linking element' that derives analogies and similitudes between the natural and artificial. Accordingly, in the aim of establishing information exchange between nature and architecture, nature is modeled through computational thinking, theory, rules and tools. Hence, computation acts as a mediatory device, which redefines the construction in addition to the knowledge of the nature model.

2.2.2. A Survey of Computational Models of Nature and Their Architectural Applications

Academic and professional research groups are observing nature's organizations, patterns and regularities in order to deduce relational, computable, algorithmic explanations of reality in rule-governed domain. These computational models systematize generative processes that define, express and structure the order in natural phenomena. It can be observed that computational models of nature have been progressing from static, isolated, simple and abstract systems towards more dynamic, comprehensive, associative, precise and complex systems. Consequently, the generative process of natural phenomena started to be regarded

[49] Günther Feuerstein. *Biomorphic Architecture: Human and Animal Forms in Architecture.* p. 21.

as a conclusion of an interrelated system, which embraces formal, material, multi-functional considerations in a non-linear information flow. Hence, in this manner system and process oriented information inherited in nature can be channelized to architecture through such an interpretation that the embodiment of computational models in architecture is more likely to show similitude of behavior rather than mere formal resemblances.

2.2.2.1. Cellular Models

One of the first attempts to construct computational models of nature is the cellular automata system. It shall be noted that cellular automata has gone through many interpretations, additions, alterations, and different visualizations; but the main idea of cellular automata that a definite rule set settles input, operation, and output cycle stayed the same. Therefore through explaining and exemplifying, cellular automata and its successors will be referred to as more like an idea for modeling rather than strictly defined and labeled systems.

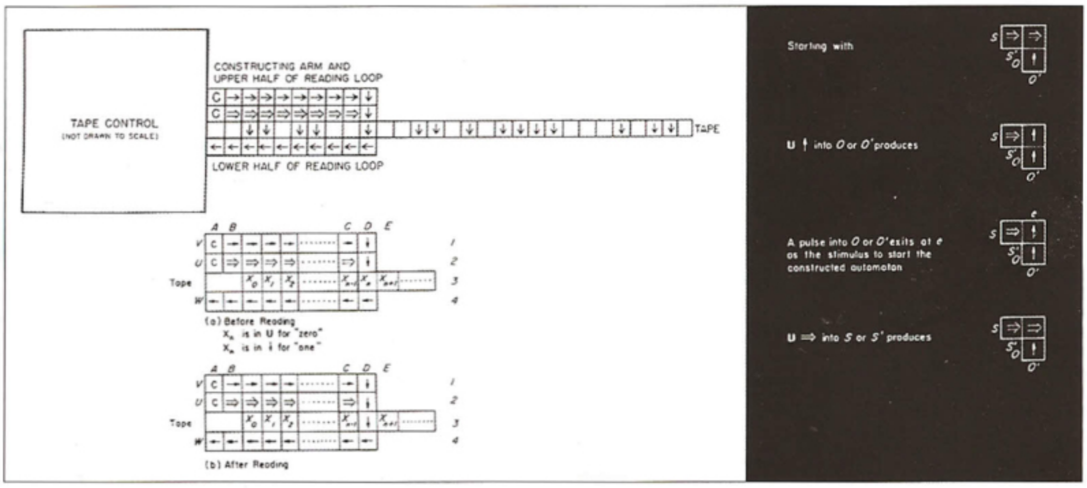

Figure 2.12 John vonNeumann’s UCC

Ingeborg M. Rocker. “When Code Matters.” Programming Cultures: Architectural Design, Vol.76, No.4, 2006. p. 20.

Cellular automata model is based on the principles of self-replication and pattern recognition, through which a cell can obtain two states (black or white) depending on the states of its neighboring cells. The initiators of the model shall be counted as the Turing Machine of 1936, Neumann’s Universal Copier and Constructor of 1940s, whereas the successors are the Game of Life of 1970, L-systems of 1968. The Turing Dimension came to be the theoretical basis by defining a computable process with a table of contents for rules and operations, a linear grid arrangement that carries the information of whether 1 or 0 in each cell, and a header which can read, write, and erase.[50] The Turing Dimension has proposed that; when a system/model with well-defined initial states, operative rules, and possible outcomes, numerous inputs can be calculated/computed through the same process.

Following the principles of the Turing Dimension, in UCC (Universal Copier and Constructor) John von Neumann and Stanislaw Ulam have studied on a non-linear two dimensional lattice grid called the tape, where the defined system works through reading the information, applying the rules, and thus generating a new population of information on the tape.[51](Figure 2.12) This process can keep on being executed several times, since the outcome tape of a previous generation is introduced again as an input. Therefore, a two-dimensional grid carrying specific information may result with unprecedented outcomes after computed recurrently for a couple of generations. Thus, the model of Neumann and Ulam have favored the complex behavior of the computational system; and at the same time the set of possible global outcomes gained diversity. Furthermore due to this complexity, simple changes in the initial states and rules causes extensive alterations in the global outcome within the same model.

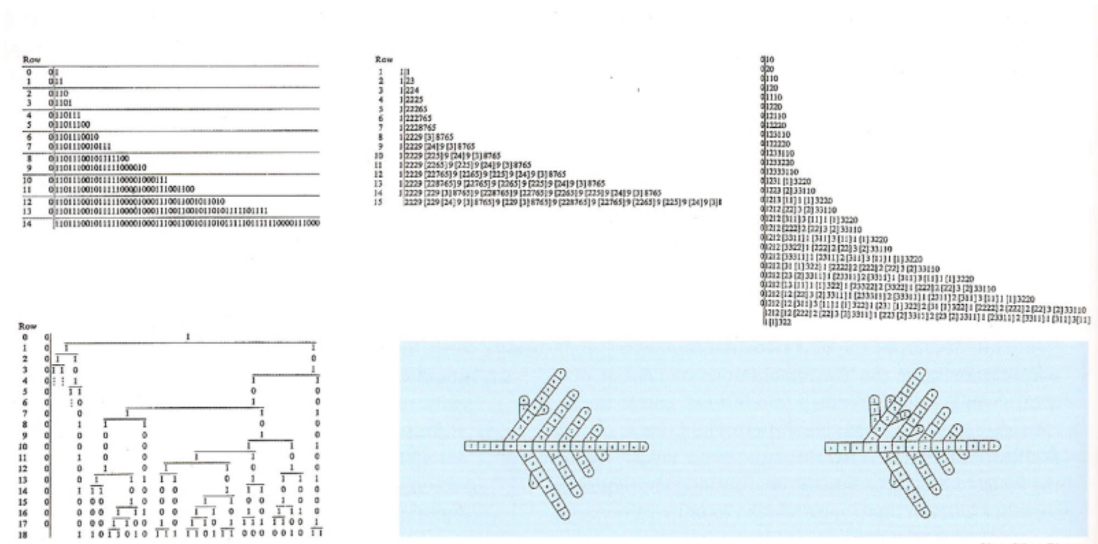

Figure 2.13 Aristid Lindenmayer, L-systems.
Ingeborg M. Rocker. "When Code Matters." p. 20.

The generative continuity of UCC, where outputs of a population become the inputs of the next generation, has been a key issue in John Conway's Game of Life. Given a grid of black and white cells, the rules operate on one cell changing its color to black or white depending

[50] Ingeborg M. Rocker. "When Code Matters." Programming Cultures: Architectural Design, Vol.76, No.4, 2006. p. 20.

[51] *Ibid.* p. 21.

on the states of its surrounding cells.[52] The Game of Life illustrates the self-organization, self-replication, and pattern recognition properties, which are common to natural phenomena. Furthermore, the Game includes the possibility to run the computational model continuously for many generations, and therefore it includes time – the data processing time – as a determinant factor of the process.

Similar to the continuous processing of Game of Life, Aristid Lindenmayer's L-systems aim to define the branching system of trees under growth. Again in L-systems, it can be observed that the defined set of rules and operations are applied to initial inputs generating populations, which are later regarded as inputs of the next generation. In L-systems the growth through processing time has a branching visual or symbolic structure instead of a diffuse two-dimensional grid; and still the previous generations are stored as a part of the global outcome.(Figure 2.13) Therefore, it is possible to perceive the repetition of the same structure at different scales in the global outcome. In a way, as many times the process is executed, as many different scales of the same structure emerges showing a fractal configuration.

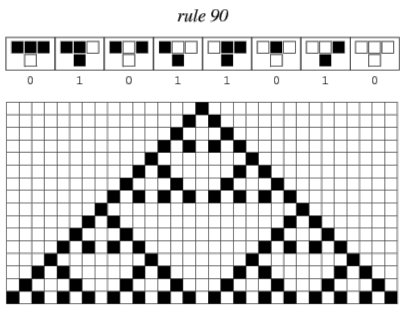

Figure 2.14 Stephen Wolfram's cellular automata studies, Rule 90.
Available from: http://mathworld.wolfram.com/Rule90.html
Last resumed at 04.09.2010

On the other hand, it can be said that Stephen Wolfram approaches cellular automata as a juxtaposition of the cellular pattern of the Game of Life and the growth structure of L-systems. He believes that cellular automata can explain and generate all types of natural and human-made organizations. In his works, the generated child is determined due to the black and white pattern of the parent cells.(Figure 2.14) Accordingly, the model is based on the simple definition of this parent-child relationship. The global pattern of growth is obtained by executing several generations. The important point of all the models deriving from the Turing Dimension is obvious in Wolfram's cellular automata studies: micro changes in the parent-child pattern relationship, differs the global pattern of the outcome. He declares: "All

[52] *Ibid.*

processes, whether they are produced by human effort or occur spontaneously in nature, can be viewed as computations."[53]

Wolfram's studies prove the versatility of computation, even in a two-dimensional and binary domain. The interpretation of the Game of Life that generates three-dimensional cellular pattern organization gives clues about what computation may imply for architectural form generation.(Figure 2.15) Regarding the diversity obtained within a limited computational model of cellular growth, it shall be tackled the unprecedented possibilities that architecture can develop through computation in three-dimensional space, initiating from a more populated initials set. Besides, these computational models constitute a significant beginning for the contemporary computational inquiries in architecture, since they are the first to introduce a visual computational algorithm breaking the previous concept of computing as numerical calculations. Ingeborg M. Rocker states "architecture is, and always has been coded."[54] Additionally, he considers computation as a non-traditional and free symbol system that enables decoding and recoding.[55] Hence, computational models enable *transcoding* the knowledge extracted from nature into the process of architectural design.

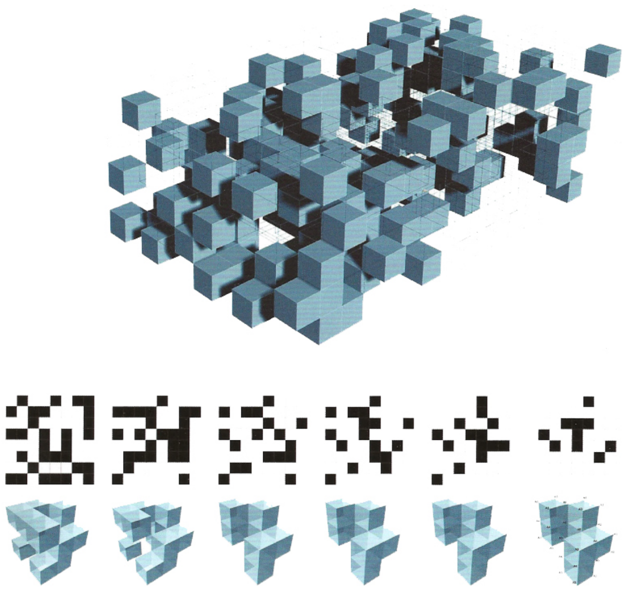

Figure 2.15 Brandon Williams/Studio Rocker, 3D Game of Life, 2003.
Ineborg M. Rocker. "When Code Matters." p. 24.

[53]Stephen Wolfram. *A New Kind of Science.* Canada: Stephen Wolfram LLC, 2002. p.715.

[54] Ingeborg M. Rocker. "When Code Matters."

[55] *Ibid.* p. 25.

A straightforward example to the *transcoding* of cell-based computational arrangements to architecture is the Mike Silver Architects' competition entry for the design of San Jose State University Museum of Art and Design.(Figure 2.16) The brick façade of the building is designed through pattern based computational models.[56] The rules of pattern generation are defined by the construction limitations of bricklaying and the light requirements inside the building. It must be considered that Cellular Automata is just one of the computational models that could *transcode* the pattern recognition and self-organization properties existing in natural organizations to architecture. Depending on the type of knowledge that is to be inherited, the computational model shall be structured, modified, and determined.

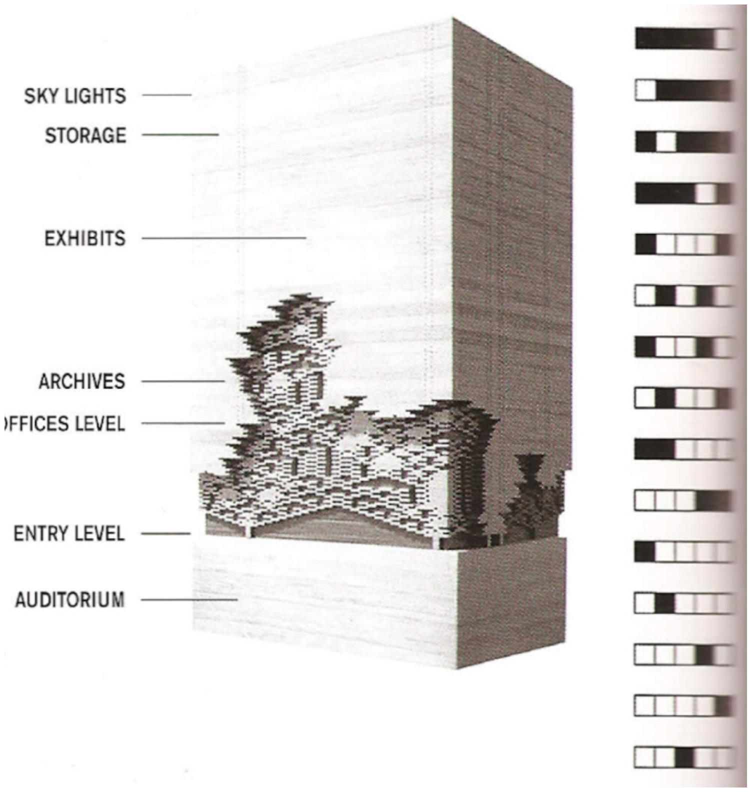

Figure 2.16 Mike Silver Architects' competition entry for San Jose State University Museum of Art and Design, 2003.

Mike Silver. "Building Without Drawings: Automason Ver 1.0." p. 48.

[56] Mike Silver. "Building Without Drawings: Automason Ver 1.0", *Programming Cultures: Art and Architecture in the Age of Software*, Architectural Design, Vol 76, No 4. 2006. pp. 46-51.

2.2.2.2. Fractal / Porous Models

In the field of computation, studies on porous natural phenomena and self-repeating patterns have been initiated by studies on fractals. Though, cellular automata and L-systems may generate similar outcomes, the distinct ‘replacement method’ for constructing fractals have flourished a parallel field of study. Fractals refer to an approach towards developmental systems that generate highly self-similar organizations. In other words, in a fractal configuration, a structural pattern reoccurs at any scale. Accordingly, there is a recurrence of a specific rule set, which is executed in loops for various generations. The replacement method involves pattern recognition, self-organization, and self-repetition in the broadest sense. Hence, there occurs a homogenous heterogeneity in the outcome pattern of fractal organizations. Koch Snowflake, Sierpinsky Carpet and Menger Sponge have been the predecessor visual explorations of fractals in two-dimensional and three-dimensional generative models. The sponge-based computational porosity models and their use in architecture have evolved in advent of the information technologies. A shift occurred in understanding porosity within architectural practice: an alteration from a static generative system towards a dynamic integrated inquiry.

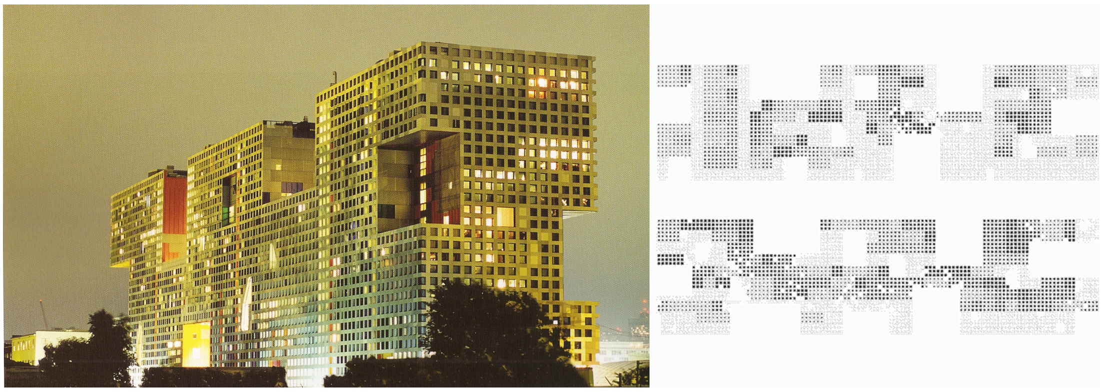

Figure 2.17 Simmons Hall, MIT Residence Hall by Steven Holl Architects, 2002. It is observable in the façade studies that a duality of heterogeneity and homogeneity has been intended to establish.

Mahadev Raman. “Sustainable Design: An American Perspective.”

The MIT Residence Hall by Steven Holl Architects resembles a Menger Sponge, which embraces variety of patterns within the self-repetition of a specific pattern at different scales.(Figure 2.17) Moreover within this configuration of uniformly distributed solid-void volumes includes channel-like airways throughout the building, which provides air circulation. Hence, the inhabitants of the building have reported no inconvenience about the heat equilibrium.[57] The airflow calculations and air-circulation behavior essentially are the interest of fluid dynamics studies. Thus, the designing process of Simmons Hall required a non-linear and multi-dimensional understanding for interdisciplinary studies.

OMA (Office of Metropolitan Architecture) has worked on the porosity property as well as the light permeability of sponges in an interior design project that has been developed for Prada. The aim of the project was to design divider panels that would provide visual privacy and daylight at the same time. Thus sponge-like panels have been obtained through using digital modeling and rapid prototyping techniques.[58] In this approach, sponges and the solid-void configuration can be regarded as the source of inspiration, which is effective in attaining architectural functions to formal sponge qualities.

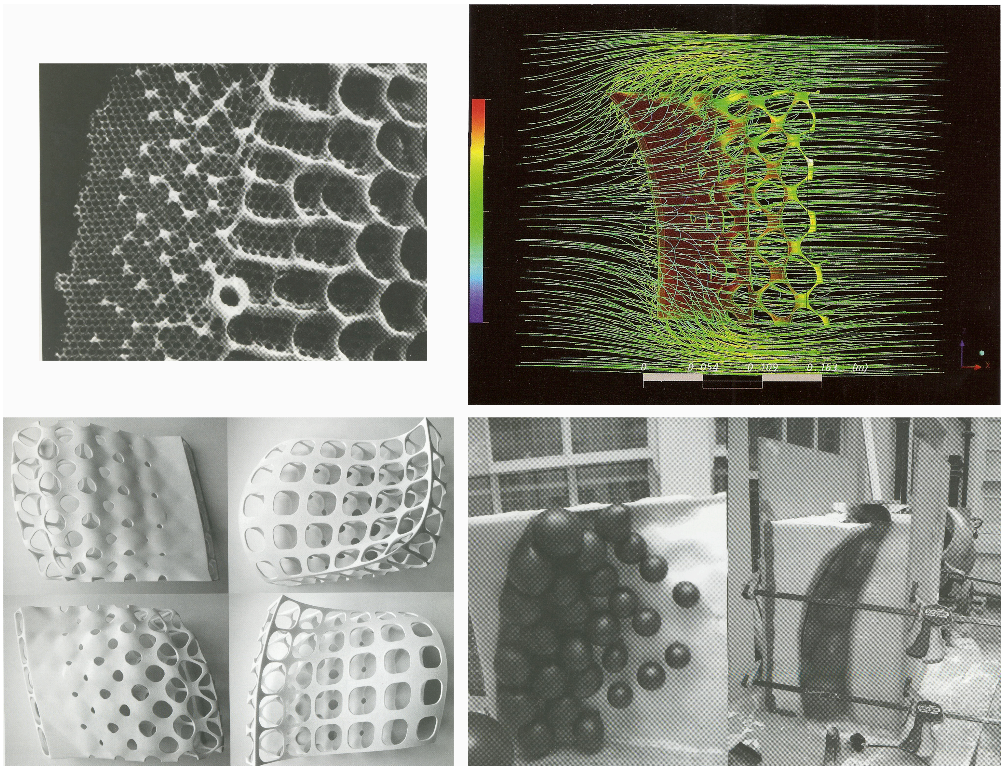

Figure 2.18 MSc dissertation project of Gabriel Sanchiz Garin at AA School of Architecture, 2007. (a) Diatome structure as the object of study from nature, (b) Computational Fluid Dynamics (CFD) analysis of airflow, (c) some of the many different morphologies generated by the developed computational model of diatome, (d) the casting process.

Michael Hensel, Achim Menges, Michael Weinstock. *Emergent Design Technologies and Design : Towards a Biological Paradigm For Architecture.* pp. 212-216.

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[57] Mahadev Raman. "Sustainable Design: An American Perspective." Chapter in *Performative Architecture Beyond Instrumentality*. Edited by Branko Kolarevic, Ali M. Malkawi. New York: Spon Press, 2005. pp. 47-48.

[58] Available from OMA website: http://www.oma.eu/
Last resumed at 13.09.2011.

On the other hand, fluid dynamics of a sponge-like porous mass surface has been the key inquiry for the research project of Gabriel Sanchiz Garin at AA School Master Program.(Figure 2.18) The structure of the project derives from a re-investigation on the shells of diatoms and skeletons of radiolaria.[59] The generative system of the porous structural surface, its components and parameters have been modeled in a computational system, where the porosity and variety of the overall form is analyzed according to its air transmittance in CFD(Computational Fluid Dynamics Systems). Moreover, the study includes a parametrically defined cast system, which is formed depending on the component proliferation and associative adaptation to a mould. Moreover, heterogeneity and vicissitude of air/ light permeability may be obtained in this highly differentiated and associatively parameterized screen wall. Michael Hensel and Achim Menges argue 'the project commences from a biological model and converges it into architectural potential.'[60] Hence, the project approaches its object of study considering its implications on architectural form and function; and concordantly function of air circulation is interpreted as an extension of several parameters integrated in a computational model.

2.3. Discourse on the Contemporary and Upcoming Explorations about the Conjunction of Architecture, Nature, and Computation

The number of examples showing the interaction between nature and architecture can be increased further more. Yet, it is since 1970s that learning from nature became an issue, and several researchers and theorists have inquired and conjectured on how the interaction between nature and architecture shall be established. Janine Benyus proposed the term 'biomimesis' to describe a new discipline that centered on learning from nature for constructing man-made organizations. Charles Jencks anticipated a 'biomorphic' movement that would influence architecture. Kevin Kelly declared our future would be a 'neo-biological' civilization where machines and buildings with life-like complexities work. And Julian Vincent argued the input of biology to architecture should be its problem solving capability instead of form and shape. Consequentially, there has been a change in the understanding about learning from nature. The major shift in the knowledge extracted from

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[59] Michael Hensel, Achim Menges, Michael Weinstock. *Emergent Design Technologies and Design : Towards a Biological Paradigm For Architecture.* Oxon [England]; New York, NY: Routledge, 2010. pp. 212-225.

[60] *Ibid.* p. 221.

nature is due to the contributions of the computational mode of modeling. Hence, once more nature is the object of interest for architecture depending on computational reinterpretations of its generative system.

In nature geometry, material, structure, function, environmental control, growth work in integration, promoting each other with feedback and feed-forward loops. Computational and algorithmic constructions can model nature including these aspects with a level of abstraction and selectivity depending on the kind of knowledge that is to be understood and explained. In this manner, the knowledge that we can extract from nature has taken on a new dimension with the introduction of computational models. From a biologist's point of view, Janine Benyus argues that humanity is living a 'Biomimicry Revolution' in various disciplines, depending on what we learn from nature now is extensively different from the past attempts of formal inspiration.[61] It is possible to go beyond inspiration and re-analyze nature as a "model, measure, and mentor" with the new methods and tools that computational thinking offers. Therefore, there occurs a revolutionary change in the understanding of nature as a model from a formal one towards a systematic one.

In 1971 Charles Jencks has predicted that architecture would go through a biomorphic movement from 1980s on, which corresponds with the period after the parametric design movement and cybernetic approach of 1970s.[62] This correspondence may not be accidental; since computational thinking has extensively changed the way we configure our ideas and analyze existing facts. Restructuring design thinking process led to rethinking natural and artificial processes; and this approach evoked a cross-fertilization of information between the natural and the artificial. However, the term 'biomorphic' refers to shape and form centered explorations in the natural world; whereas computational models of natural or artificial organizations include additional aspects more than form.

Systems of nature possess the characteristics similar to the architectural ones. Kevin Kelly declares that natural phenomena are the major guide for architecture in terms of their complex organizations, and generative processes. He explains his assertion for a future 'neo-biological civilization':

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[61] Janine M. Benyus. *Biomimicry: Innovation Inspired by Nature*. New York: William Morrow and Company Inc. 1997. p. 2.

Benyus is the first to define the word biomimicry as "nature as a model," "nature as a measure," and "nature as a mentor".

[62] From the illustration which chronologically maps down the past and possible future movements in architecture. Charles Jencks. *Architecture 2000: Predictions and Methods*. London: International Thomson Publishing, 1971.

> "By extracting the logical principle of both life and machines, and applying each to the task of building extremely complex systems, technicians are conjuring up contraptions that are once both made and alive...For the world of our own making has become so complicated that we must turn to the world of the born to understand how to manage it. That is, the more technical we make our fabricated environment; the more biological it will eventually have to be if it is to work at all. Our future is technological; but it will not be a world of gray steel. Rather our technological future is headed toward a neo-biological civilization."[63]

Ever since computers and computer aided fabrication tools are a part of the design and construction process, there is a need to systematize/model this complex process. Serving this requirement, the generative processes of natural organizations have the potential to lead architectural design processes with their non-linear relations and multi-dimensional dependencies.

In addition to the dynamic and complex process that is common to both natural and architectural organizations, architecture bothers with life-like functions such as breathing of the building, the day light absorption, water collection, growth, structural stability. Thus, the processes of natural phenomena have an aim of problem solving. Julian Vincent adds that nature's input to architecture should be evaluated in terms of its problem solving capability instead of solely its form and shape. According to Vincent, the models of nature shall approach form and shape as a parameter instead of an end product.[64] In this manner, architecture can learn from the *becoming* of the natural, and use this knowledge in *making* the artificial.[65] Therefore, for proper similitude between nature and architecture, their models shall be directed by both the definition of the problem and the solution process. To put it differently, computational models of nature shall have a defined input, operation, and output cycle - initial conditions of the problem, the solution oriented operation, and the expected conclusion. In this manner, the initials, processes and outcomes are all structured in the model.

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[63] Kevin Kelly. *Out of Control: the rise of neo-biological civilization.* Reading, Mass.: Addison-Wesley, 1994.

[64] Julian Vincent. "Biomimetic Patterns in Architectural Design." *Patterns in Architecture: Architectural Design*. Vol 79, No 6, 2009. p. 81.

[65] *Ibid*. p. 78.

Bruce Mau lays stress on the significance of process in design:

> "***Process*** *is more important than outcome.* When the outcome derives the process we will only ever go to where we've already been. If process drives outcome we may not know where we're going, but we will know we want to be there."[66]

However it shall be questioned if within computational models the inputs, the process, and the outcome are equally significant. Since through constructing a computational model, each needs to be well defined but not identified.

Consequently, the tension between the process and the product seems to be equally distributed in a computational model, where broadly inputs, operations, and outputs are well defined in the systematic construction. Therefore, the modeler needs to have an idea of *what* will be generated and *how* it will be generated, even if he doesn't have an exact image. In this respect, the architect shall question the outcome as much as the process of natural organizations, since they are intertwined and dynamically interacting in a computational model. In fact, the whole process of biological growth is governed according to a solution and leaded towards a goal. Today architecture, as well, must know what kind of knowledge and solution it wants to obtain from the computational models of nature. Otherwise, it is inevitable for architectural research to remain inconclusive or continue searching disjointedly until it comes across a worthy solution.

Computation presents thinking modes and mediums, which lead to new understandings and explanations of our environment. Natural and artificial organizations are re/configured and re/modeled in terms of their generative processes, where relations, dependencies and information flow are considered as crucial constructive determinants. Consequently, architectural products are appraised to be conclusions of such generative processes; and architectural design is regarded to comprise the design of the process rather than an end-product. Through such a resolution and approach, natural organizations turn to be a major source of learning for architecture that instructs about complex, dynamic, and ductile systems and associative knowledge management.

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[66] Bruce Mau. *An Incomplete Manifesto for Growth*. 1998. Available from: http://umcf.umn.edu/events/past/04nov-manifesto.pdf Last resumed in 20.05.2011.

CHAPTER 3

MODELING NATURE THROUGH COMPUTATIONAL THINKING

The relationship/association/correlation between architecture and nature is shaped by *theory*, which provides the foundations and structures of thinking, and *method*, which provides tools for practicing. Moreover, theory and method are interconnected; they are mutually promoting and enhancing each other in the process of systematizing both natural and architectural organizations. As theoretical framework proposes the reasoning for knowledge constitution including the boundaries and extensions of thinking, it imposes a method for materializing the ideas. Vice versa, the method advances or strengthens the theory, as it orientates a certain way of thinking within the restrictions and potentials of specific tools and modes of representation. In other words, the theoretical framework and methodological constraints collectively construct the *model*s that will explain, comprehend, and interpret the researched object of study. Through these models, which are constituted by theory and method, knowledge may be analytically *translated* from one domain to another distinct domain of knowledge.[67]

Similarly, in the cactus studies that are to be discussed more in detail in the following chapters of this thesis, the model is driven by both the modeling literacy and method, and the theoretical construction and conceptualization. For instance, the modeling medium of Rhinoceros Monkey Script Editor works with a library of commands, which has its own limitations and potentials that determine the precision and accuracy of the model. The scripting literacy leads and restrains the algorithmic structure of the generative process that defines the form generation and relatively performance of the cactus. The parameters and variables of this algorithmic system, their dependencies and relations constituting the global information flow are influenced by the modeling medium. Additionally, the theoretical and conceptual framework of computation establishes the modeling interface, and explanatory system, as well as the scope and comprehensiveness of the cactus model. The consideration

[67] Julian Vincent. "Biomimetic Patterns in Architectural Design." *Patterns of Architecture: Architectural Design*. Vol 79, No 6, 2009. pp. 74-81.

of computation as a means of transcoding, conducts the cactus model to appeal both to the natural organisms and the architectural possibilities.

In the case of architecture and nature, the models that constitute the knowledge exchange have evolved and altered extensively since Antiquity. Until now and still today, mathematics and mathematical theories have formed the basis of these linking models.[68] Mathematics has experienced several theorems, systems and logical constructions that concluded with diverse theories. Hence, mathematical models, which translated natural knowledge to architectural studies, have extensively altered through time, as they indicated a wide range of propositions for such a translation: proportional, geometrical, Cartesian, calculus-based, etc. It should be noted that models are one of the primary requirements for a knowledge translation process between two distinct domains, since they are abstract systems to understand and interpret the objects of interest. Accordingly, modeling comprises a learning and discovery process for architectural practice, either it includes formal, environmental, systematic, or interactional aspects of a natural phenomena.

Architectural approaches, which regard nature as a contribution (constraint/ input/ companion/ associate) to architectural design, can be broadly grouped under two. These two distinct ways of interacting with nature can be encapsulated in terms of their interest in the 'existing form' and the 'becoming of form'. One perceives nature from a solely formalistic and imitative standpoint, which may include a wide range of art works from floral Corinthian column ornamentations of Antiquity, Rococo style curves and decorations, to the contemporary formal explorations in architectural products. Today, an extension of such an approach focuses on producing soft and 'impressive' forms, which can be visualized and manufactured by virtue of the technology and tools that computers offer.

On the other hand, the other approach acknowledges nature as a source for learning, which includes a wide range of works from the anthropomorphically proportioned Greek temple columns, Francesco DiGiorgio's anthropomorphic plans, to Gaudi's suspension models to the contemporary research on rule based architectural processes. Throughout history, mathematics, geometry, and scale models were interfaces that served the process of learning, while they enabled/ shaped/ systematized models of nature and thus the method of extracting knowledge and conveying it to architecture. Nowadays, computation became the accepted thinking mode for analyzing nature, constructing systematic models and interpreting these models for generating architectural design. As computational models are capable of expressing complex natural processes with their non-dimensional characteristics, relations

[68] Antoine Picon. "Architecture and Mathematics: Between Hubic and Restraint," *Mathematics of Space*: Architectural Design, Vol 81, No 4, 2011. pp. 28-35.

and dependencies, they provide more advanced and integrated knowledge input from natural organizations to architectural buildings. At present, the underlying generative system that emerges natural form can be represented in a comprehensive computational model in respect to the structural stability, material performance and efficiency, and problem solving qualifications. Correspondingly, within this approach, the reflection of nature in architecture has evolved in a great extent from analogy towards similitude.

The critical tension between these two separate approaches is fundamentally related with the two separate interpretations of typology. William Braham differentiates typology from its postmodern acceptance as "a model-to-be-copied" and discusses typology as "a generative tool that is a means of rationally conceiving new building forms".[69] Braham elucidates the critical tension between these two understandings of typology with the opposition between standardization and artistic freedom: type as a "fixed historical configuration" and type as a "generative idea".[70] The understanding and application of natural knowledge in architecture similarly depends on such a contradicting understanding of nature: nature as an image or form to copy directly, to imitate or nature as a model of generative complex systems.

Moreover, the gap between these two insights of nature in architecture has currently widened up depending on their interpretations of internalizing computation. The former accepted computer and computer-based technology as a tool for obtaining end products, visualizing and exploring un-orthogonal geometries and organic forms resembling the natural. The latter, on the other hand, internalizes the inner logic of computers and computational thinking as a basis for analyzing the generative process belonging to natural organizations, and then constructing integrated models that would systematize architectural design. In such an approach, computation turns out to be an interface for channelizing the dynamic and complex processes of nature to architecture. Therefore, the role of the architect has altered from designing an end product towards designing the process.

Computation has introduced new modes of thinking, logical relations and reasoning schemas to us. In this respect, what kind of information we obtain from our environment through observations and analyses, and how we constitute knowledge with this information have been rewritten. Within computational thinking, we consider processes as crucial for constituting knowledge through computational models, which are complete, comprehensive, integrated and simple/complex systems that explain natural and artificial phenomena.

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[69] William Braham. "After Typology: The Suffering of Diagrams". *Contemporary Processes in Architecture :Architectural Design*, Vol 70, No 3, 2000. p. 10.

[70] Ibid.

Correspondingly in this thesis, knowledge constitution is considered as the conclusion of a mutual relationship between theoretical framework and factual novelty. Thus, it will be argued in the case study on cacti that a new sort of knowledge (process-based) can be extracted through computational models of natural phenomena. Hence, computational models of reality are manifestations of the theory of computation. Likewise in Chapter 4 and 5, it is observable that rethinking and reconstructing cacti within computing theory and in computational medium evokes a process-based generative and parametric model, while at the same time the established model of cacti presents and manifests the principles of computational and algorithmic thinking. In other words, the computational cacti model shows the theoretical construction with computation both in the production of the model and in the structure of it.

Computational models of nature are explicit and complete generative systems, thus they promote the glass-box understanding of a complex, dynamic, and integrated process for form generation. Within the scope of thesis, the processes of natural phenomena are proposed to be transcoded as architectural design processes through computational modeling. Throughout the transcoding practice, computation acts as a mediatory link between nature and architecture, while the translation and linking to a computational process is structured in *decoding* and *encoding* loops.[71] Computation as transcoding first decodes the information of nature under a computational syntax such that the data has a universal language; then encodes this information for generating architectural design. In this manner, the universal domain of computation flourishes a trans-disciplinary field of inquiry on nature and architecture.

Through the cacti studies in Chapter 4 and 5, the interrelated association of form, function, and performance has been decoded and encoded through computational thinking and within the limits and potentials of computational modeling mediums. It shall be noted beforehand that the cacti model illustrated in this thesis stays limited within the domain of architecture, though a computational model could have been more comprehensive and trans-disciplinary. The study in this thesis unleashes the generative algorithmic system of cactus form and geometry, regarding the interrelation of form to performance that will fulfill the functional requirements for self-cooling, self-shadowing, and water collection. Yet, the model possesses the possibility of being developed towards more complex and dynamic systems, if several authors that have separate disciplinary backgrounds conduct the modeling process.

[71] Decoding and encoding is well defined in the book:
Ingeborg M. Rocker. *Re-Coded: Studio Rocker.* Berlin: Aedes, 2005.

Knowledge constitution concerns how we acquire specific data from our experiences of natural or artificial phenomena. It is a mutual effect of what we see and how we understand it; it is a consequence of both the physical reality and the method of explanation. In other words, information experienced in the physical world is comprised as knowledge through an associated constructive theory. Charles Rickart emphasizes that human brain operates with structures (such as mathematics, language or any systematic representation), which play an essential role in thinking and understanding.[72] He argues that structures make a situation or data intelligible.[73] Thus, numerous types of information that are implanted in natural and artificial phenomena become explicate as they are redefined and reconfigured under a structure, through a systematic reconstruction.

In the Renaissance for instance, a revolutionary new process was proposed to examine the world and to extract the information it embodied: the scientific method, which is based on empirical evidence, mathematics, and mechanical philosophy. The interest for explaining the complexity of life brought forth researches on the underlying logic; these researches explained natural phenomena with mathematical, geometrical and physical principles in a complete *system*, a structure.[74] The enthusiasm for knowledge of the era was led by the mathematical theory, which led to significant discoveries in astronomy, physics, biology, and anatomy. With these contributions, the vision of the world, the way we see and comprehend natural phenomena changed extensively,[75] comparable to today's computation based practice.

Computation presents new thinking modes and mediums to analyze, consider, and understand natural and artificial phenomena once again. For instance, a computational understanding of cacti areole configuration differs from previous approaches. Phyllotaxis (leaf/seed arrangement in plants) has been defined before with mathematical and geometrical formulas. Yet, these explanations have been assessed to be two dimensional, numerical, undynamic, and to have long calculation time. Moreover, a mathematical explanation

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72 Charles Rickart. "Structuralism and Mathematical Thinking." Chapter in *The Nature of Mathematical Thinking* edited by Robert J. Sternberg and Tali Ben-Zeev. Mahwah, NJ: Lawrence Erlbaum Associates, 1996. pp. 285-300.

73 Ibid. p. 286.

74 Hubert Damish. *The Origin of Perspective.* Translated by John Goodman. Cambridge, MA: MIT Press, 1994. p. xvi.

In the case of studies on perspective, "geometry as a rational foundation for *construzione legittima"* became the explanatory medium to construct the system through Renaissance.

75 Jerry Brotton. "Science and Philosophy". *The Renaissance: A Very Short Introduction*. OUP, 2006.

establishes an atomistic definition of solely phyllotaxis. On the other hand, in a computational explanation of cacti areole configuration, the model is comprised of a complete system with an algorithmic structure. A computational explanation comprises a holistic perception of the entire cactus plant interpreting the phyllotaxis of areoles in relation to the overall form of the cactus body, and its water collecting, self-shadowing performance. Thus, the structure of computation constitutes a new type of knowledge about cacti areoles, which unleashes the underlying generative process and its interrelated complex information flow schema that relates several properties of the cacti organization as parameters leading to a global system.

A theorem grows into a theory, getting stronger and more legitimate as it penetrates into studies within other disciplines. As the way things are analyzed and explained is reshaped by the incoming theory, it means the previous theory is found unsatisfactory for further research. Vice versa, as theory shifts occur, the way we see and understand the universe changes.[76] In the first half of the 20th century, the invention of computing machine was the idea, which cultivated and got advanced while it jumped through many disciplines. Now it happens to be the foundations of the computational paradigm, which replaced previous theories for explaining many natural phenomena due to its integrated and comprehensive attribute.

Theoretical frameworks can be directive and obstructive at the same time. As the accepted theory proposes a model and a scientific method for the research and study, it also suggests automatically the constraints and limits of the work. Kate Nesbitt emphasizes the speculative, anticipatory, and catalytic character of a theory and asserts, "new theories arise to account for unexamined and unexplained aspects of the discipline."[77] If an incoming theory is elucidative, influential, and comprehensive enough to induce several disciplines and create an extensive change in their mind-set, it creates a paradigm shift.

Thomas Kuhn declares, in order for a theory or scientific achievement to be a paradigm, it needs have the two properties. First, it needs have a group of successors, who prefer to practice under the corresponding theory rather than the competing ones. Secondly, it has to

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[76] *Ibid.* p. 53.

Kuhn declares that "Assimilating a new sort of fact demands a more than additive adjustment of theory, and until that adjustment is completed – until the scientists has learned to see nature in a different way – the new fact is not quite scientific at all."

[77] Kate Nesbitt. "Introduction." *Theorizing a New Agenda for Architecture: An Anthology of Architectural Theory 1965-1995.* Edited by Kate Nesbitt. New York: Princeton Architectural Press, 1996. p.16.

be ‘open-ended’ and applicable to explain problems belonging to all fields of study.[78] Kuhn declares that a paradigm provides models and patterns.[79] Accordingly, the successors carry on their scientific activity regarding the same rules and standards. It can be questioned where computation does stand between theory and paradigm considering a highly populated group of successors and its widespread acceptance in various fields of study.

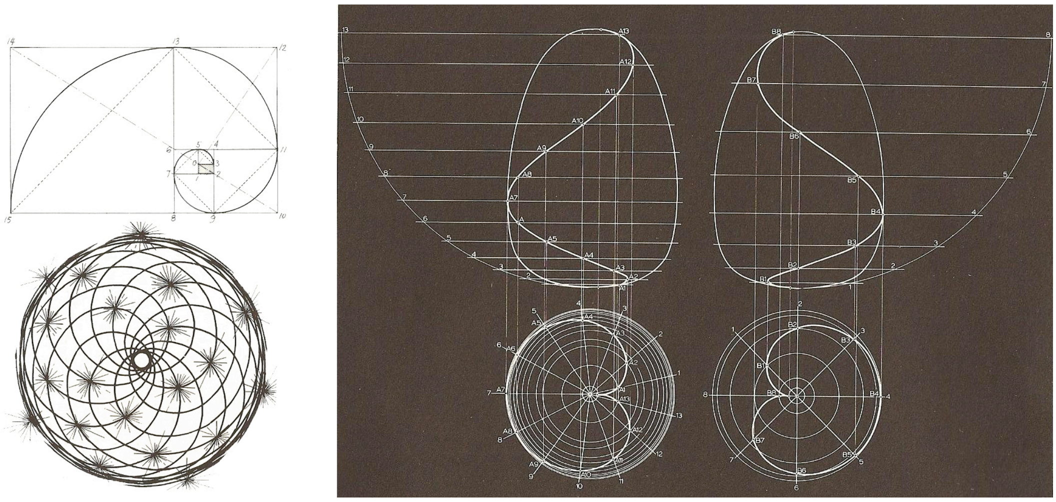

Figure 3.1 The three-dimensional Golden Spiral resolution of the Jeffrey Pine.

György Doczi. *Power of Limits: Proportional Harmonies in Nature, Art, and Architecture.* Boston: Shambala, 2005.

Now with computational thinking, process (relations) gains importance rather than states (equations), to describe a system where non-dimensional algorithms work, and where numerical mathematics is replaced by computational operations. In a computational description of the world, there is a continuous space-time-information flow which proposes dynamic processes rather than static, multiple equilibriums in movement throughout the system rather than a single state of equilibrium, topological properties rather than numerical, multi-dimensional relationships and dependencies rather than fixed rules.[80] Consequently, there occurs a new vision of the world and its systems: the information we see and extract modifies, since computation as an interface offers new means of interpretations and representations of reality. In this way, the theory and media of computation are setting the nature and its systems again.

78 Thomas Kuhn. *The Structure of Scientific Revolutions*. p. 10.

79 *Ibid*. p. 23.

80 Paraphrasing the table structured by Manuel Gausa. “Dynamic time - <in>formal order: <un>disciplined trajectories”, *The Metapolis Dictionary of Advanced Architecture*. Barcelona: Actar, 2003. p. 626. First published in *Quaderns* 222, 1999.

In this thesis, the commonly known depiction of phyllotaxis (leaf/seed arrangement) by the well-accepted Fibonacci series and Golden Section spirals has been re-set in the proposed computational model of cacti. Further in thesis, in Figure 5.1 and 4.10, it is illustrated how the phyllotaxis of areole configuration on a cactus body is resolved in an associated and integrated computational system. Through computational thinking and mediums, the areole configuration of cacti has been redefined with simple relations, dependencies and computational operations, which compose a more dynamic, parametric, typological, flexible system.

Stephan Wolfram argues that a new kind of science is emerging with computational thinking: a reconsideration of natural world depending on the more general types of rules that express the underlying process.[81] The considerable difference of computation from traditional mathematics is that it is based not only on static equations or numerical formulas to explain a system, but it focuses on basic relations, universal dependencies to describe complex systems with dynamic processes. The universality of computation is considered by its degrees of freedom: the flexible language of rules and logical procedures that can instantly transform the conclusion from one to another.[82] In the cactus studies, the cactus species have been analyzed in order to formulate a motor diagram, which is derived from its isomorphic properties. Thus, the computational model gained the capacity to generate numerous types of cactus through one generative system. Therefore the difference offered by universal process of computation makes it possible to explain and reformulate all kinds of artificial and natural phenomena.

The current trend in contemporary architecture approaches ‘process’ in terms of elucidating the structure of an interactive knowledge constitution with guidance of information technologies, computational thinking. Through this search for a revised/remodeled architecture, which is defined by and applied through computational operations and media, natural form generation turns into a major lead to configure information flow, and to

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[81] Stephan Wolfram. *The New Kind of Science.* Canada: Wolfram Media, 2002. p. 5.

In this study on cellular automata, Wolfram summarizes his departure from traditional mathematical explanations of natural and artificial phenomena: “One of the most surprising discoveries of this book is that in fact there are systems whose rules are simple enough to describe in just one sentence that are nevertheless universal. And this immediately suggests that the phenomenon of universality is vastly more common and important –in both abstract systems and nature- that has never been imagined before.”

[82] Mike Silver. “Towards a Programming Culture in the Design Arts.” *Programming Cultures: Art and Architecture in the Age of Software: Architectural Design*, Vol 76, No 4, 2006. pp. 5-11.

understand the complexity of dynamic systems. Philip Steadman, whose work centers on the topic of natural analogy in architecture, points out:

> "What *has* happened over the intervening thirty years is that there has been a great flowering of new theory in architecture and design, looking not just to understand and imitate natural *forms*, but seeking insights at deeper levels into biological *processes*, from which designers might derive *models* and *methods*."[83]

Philip Steadman's motivation for revising his book "Evolution of Designs: Biological Analogy in Architecture and the Applied Arts", which was first published in 1979, is mainly the change in the way that architecture is learning from nature. This change is primarily triggered by the recognition of computation as a constructive theory and conceptualization. Computational explanations of natural and artificial phenomenon are deeply bounded up with the process of theoretical construction. Theory acts as a structure for configuring the underlying system belonging to the subject of investigation. John H. Holland elucidates theory as:

> "Without theory, we make endless forays into uncharted badlands. With theory, we can separate fundamental characteristics from fascinating idiosyncrasies and incidental features. Theory supplies landmarks and guideposts, and we begin to know what to observe and where to act."[84]

Theory is the most determinant factor of how we systematize ideas and analyze existing situations. It offers a 'model' for mental constructs, the way of thinking in addition to the infrastructure and the probable set of building stones needed for this construct. In a sense, theory designates our perceptual selectivity, subject to the mode of reasoning it proposes. In other words, the complex and massive information cloud that is embedded in natural and artificial phenomena is simplified, clarified and organized by a constructive theoretical framework. The aggregation of methodical knowledge under distinct disciplines - the departmentalization of professions and academic studies - is the result of a process similar to perceptual selectivity. A commonly analyzed natural asset can be given as an example to elaborate how several research areas approach the same object of study under distinctive theories and models, and consequently how they extract different types of knowledge from it. Nautilus will conjure disparate ideas in the mind of a geometrician, a biologist, a marine scientist, a chemist, and an architect. They each analyze the nautilus under a distinctive

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[83] See Philip Steadman. *Evolution of Designs: Biological Analogy in Architecture and the Applied Arts*. Oxon: Routledge, 2008. First Published at Cambridge: Cambridge University Press, 1979.

[84] John H. Holland. *Hidden Order: How Adaptation Builds Complexity*. Reading, MA: Helix Books, 1995. p 5.

theoretical framework, with a peculiar methodology and constructive language.[85] Therefore, they possess different thinking modes and constructive models; thus they derive distinct types of information from a common object. Likewise, the cactus plant should conjure up new kinds of knowledge and information for architectural inquiry, when it is inquired within an architectural approach and through computational models.

Even in the historical development of one discipline, theory shifts create modifications or fundamental changes in the way a specific phenomenon is analyzed and explained. As an example, the field of physics has gone through many breakthroughs. By this meaning that, physics observes natural phenomena and intends to uncover the underlying patterns and principles that regulate these natural phenomena.[86] The theoretical framework is the decisive navigator of such a study, wherein understanding and explaining the universe as a system is the major concern. Hence, the field of physics models natural organizations and phenomena under a theory, which provides the mode of thinking and reasoning, and through a method, which embraces the specific structure of mathematical notations and principles. Whenever a new theoretical framework replaced the traditional one in physics, the old justification of a phenomenon – thus its model - has altered or thrived.[87]

On the other hand, theoretical breakthroughs do also result from an apprehension that the current model of a phenomenon constructed under the up-to-date modes of thinking and methods, is not adequately explaining the mechanics and dynamics of the natural system in question. Michael Hays states that theory is "an appetite for modifying and expanding

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[85] Seashells as a geometrician: Ian Stewart. *Nature's Numbers: The Unreal Reality Of Mathematics.* Basic Books, 1995.

Seashells as a biologist: D'Arcy Thompson. On Growth and Form second edition, vol I&II, Cambridge University Press, Cambridge, 1959.

Seashells as an architect: Semra Arslan Selçuk, Arzu Gönenç Sorguç. A Parametric Approach To Biomimesis: Proposal For a Non-Dimensional Parametric Interface Design.

[86] H.D. Young, R.A. Freedman. *University Physics with Modern Physics*. 11th Edition. Addison Wesley, 2004. p. 2.

The word 'physics' is derived from the Greek word physis (*φύσις*) which means nature. Hence, since Antiquity physics is considered as the science of in animate nature with the goal of explaining the natural phenomena by its governing systematic order.

[87] For instance, the Scientific Revolution in the 15th century raised from the development of a mechanical philosophy which was nourished by nathematics and the eager to find orders and build relations underlying in natural phenomena. Thus, since the previous explainations have stayed inadequate, science has underwent throuugh a revolutionary change in understanding systems of the world.

Alfred Rupert Hall. *From Galileo to Newton*. New York: Dover Publications, 1981.

reality, a desire to organize a new vision of a world perceived as unsatisfactory or incomplete".[88] It must be noted that the desire for reconstructing the reality on a new system does not only result from the developments within the boundaries of a discipline, but it comes along throughout the collective studies of various disciplines. The collective character of theoretical construction can be summarized under 'hermeneutical epistemology', which will be referred to as the knowledge construction as an outcome of interconnected relations and dependencies between several disciplines in a non-linear arrangement.[89]

In a hermeneutical knowledge constitution, scientific studies are developed within the contribution of various fields of knowledge, and through multi-dimensional loops of knowledge exchange. Thus, the accumulation of knowledge results from a helical information flow and collaboration, rather than a linear one.[90] The collective studies on the discovery and identification of 'DNA' are illustrative examples of such scientific study structures. The discovery of DNA is most likely to be related with the developments occurring in the disciplines other than biology. Corresponding to the declaration of DNA as the transforming principle, in the field of computer science it was enunciated that a well-defined system with a set of initials, rules, and outputs could operate a variety of complex calculations and end up with alternate outcomes. These emerging ideas had most probably triggered the search for underlying principles that would define the difference, uniqueness, and as well similarities in nature. After a long period of researches, contemporary notion of 'DNA' has been specified collectively by a group of scientists.[91] As it is known, DNA is a

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[88] K. Michael Hays. "Introduction." In Michael Hays ed., *Architecture Theory Since 1968*, an anthology. Cambridge MA: The MIT Press,1998. p. xiv.

[89] For forther reading on hermeneutics as a subject of epistemology:
Zeynep Mennan. "Theory on Borderlines: A Collective Experience and a Free Market". *Shifting Borders, Negociating Places: Cultural Studies and the Mutation of Values(s)*. Edited by B. Adkins and D. Bennato. Rome: Bordighera Press, 2006. pp. 65-85.

Merold Westphal. "Hermeneutics as Epistemology." *Blackwell Guide to Epistemology*. Edited by John Greco and Ernest Sosa. Massachusetts: Blackwell Publishers, 1999. pp. 415-435.

[90] Zeynep Mennan. "Theory on Borderlines: A Collective Experience and a Free Market".
[91] Ralf Dahm. "Frederick Mieshler and the Discovery of DNA." *Developmental Biology*. Vol: 278, Issue: 2, 2005. pp. 274-188. Available from:
http://www.sciencedirect.com/science/article/pii/S0012160604008231. Last resumed at 09.09.2011.

The major contributions can be summarized as:
In 1865 Gregor Mendel, after his experiments of breeding, suggested that there are inherited specific laws determining the traits of species. Later Frederick Mieschler isolates DNA for the frst time, as a nuclein(1871). In 1919 Phoebus Levene suggested a nucleotide unit, which existed in all the nuclei's of the cells. The following investigations of Frederick Griffith on transforming principle in 1928, leaded Oswald Avery and his colleagues (Colin MacLeod and Maclyn McCarty) identify transforming principle as DNA in 1944. Avery suggested that DNA carried genetic information, which is ruling the growth and form of the organism. In 1952 James Watson and Francis Crick revealed the double helix

string of molecules that stores information about the corresponding living being in the nucleus of every cell. In a way, DNA can be interpreted as a script that is consisted of symbols and codes, which determines the growth, form, function of each cell and entire organism. Thus, it may not be a coincidence that DNA has been discovered in the same period with the arising of logical positivism in philosophy, the invention of Turing Machine, and proliferation of algorithmic thinking.

It shall be mentioned that the research of this thesis - cactus should be analyzed in such a hermeneutic approach, including numerous disciplines that would collectively establish a working model depicting various properties and qualifications of its assets. However, within the scope and limits of this thesis, the interrelated properties and qualifications of cactus will be intended to be explained in a complete, systematic, computational process as much as possible with an architectural background.

The engagement of biology with computation emerged in new research fields such as computational biology, bioinformatics, and molecular biology. Since mid 20th century, molecular researches in biology comprised computer modeling tools and techniques. The visual digital models, which forced the modeler and investigator think about the geometry and form of molecules, added another dimension to the quest of a chemical explanation.[92] Along with artificial intelligence, machine learning, robotics, and information theory; the discipline of biology has been redefined as 'information science'.[93] Therefore, while computational thinking and tools have reorganized the research themes and techniques of scientific studies, a paradigm shift occurred in biology.[94] Initially, computers have been used in biology as data storages and calculating devices that proposed relatively short processing time.[95] Afterwards, they turned into interfaces for inquiries acting as extensions of the mind.

In architecture, the early usage of computers was limited; they were perceived merely as tools for drawing and visual representations. Architecture undergoes an extensive change,

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structure of DNA. The studies have continued further more for acquiring more precise definitions and models.

[92] Timothy Lenoir, Casey Alt. *Flow, Process, Fold: Intersections in Bioinformatics and Contemporary Architecture*. p. 3. Available from: http://www.stanford.edu/dept/HPST/TimLenoir/Publications/Lenoir_FlowProcessFold.pdf Last resumed at 05.09.2011.

[93] *Ibid*. p. 8.

[94] *Ibid*. p. 6.

[95] *Ibid.* p. 9.

since it began to embrace computational thinking as the major deriving force that structures the design process and thus regulates the architectural product.[96] At present, computers have been acknowledged in architecture as system processors. Since therefore, the usage of computers in design departed from being solely representation tools towards being a medium for rule-based thinking and generative systems in architectural inquiry. Correspondingly, architecture began to be interested more in the design process rather than the end-product. The design process embraces various phases including the analysis, evaluation, structure, mechanics, material, construction, manufacturing and assembly of building elements. Through architectural design, the relations and dependencies between these different phases and knowledge areas follow a complex, non-linear, and multi-dimensional information flow that is nourished by continuous feed backs and forwards. Such an understanding and practicing of design process constitutes a transdisciplinary design environment and inter-relational division of labor, where architect turns out to be the designer of the system, the generative process.

3.1. Towards Glass-Box Processes: Uncovering the Generative Process of Design and Nature

The architectural design process began to be scrutinized in terms of its complex systematic setup with the emergence of computational thinking. Through the researches about the design procedure that the designer follows implicitly or explicitly, the terms ‘black-box’ and ‘glass-box’ processes/models have emerged.[97] Glass box design processes are transparent, explicit, rational, clearly structured (complex) models. Set and graph theories (mathematics of classification and structural relationship) are essential directories for such a model

[96]Michael Weinstock. “Morphogenesis and the Mathematics of Emergence.*” Emergence: Morphogenetic Design Strategies: Architectural Design*. Vol 74, No 3, 2004.

[97] Researches on design methods studies, and the development of the terms “black box” and glass box” can be found mainly in the following references:

İlhan Tekeli. “Tasarım Sürecini Bilimselleştirme Çabaları.” *Mimarlık*. 148, 1976/3. p. 59-62.

Nigel Cross *et al* (eds.) *Analysing Design Activity.* John Wiley & Sons, 1996.

Christopher Jones. “The State-of-the-art in Design Methods.” *Design Methods in Architecture*, edited by G. Broadbent and Anthony Ward, Architectural Association Paper Number 4. New York: 1969. p. 193-197.

Tonguç Akış. Thesis named “Teaching / Forming / Framing A Scientificallt Oriented Architecture In Turkey Between 1956 – 1982.” Supervised by Mine Özkar. Ankara: METU Department of Architecture, 2008.

construction where parameters, variables, relations, and dependencies are well defined.[98] On the other hand, in a black-box design the only known components are the input and output; the designer doesn't have comprehension about the process that generates that outcome.

Terzidis emphasizes the existing change of the architect's role with his interpretation of algorithmic architecture from "architecture programming" to "programming architecture".[99] This equivocation with a minor variation refers to a major difference in how computation is integrated in the design process. Terzidis proposes: "By using scripting languages designers can go beyond the mouse, transcending the factory-set limitations of current 3D software. Algorithmic design does not eradicate differences but incorporates both computational complexity and creative use of computers."[100] In such a manner, the architect is not constrained within the limits and commands of the presented computer program, which is actually imposing the model for structuring the design process. Instead, he is capable of doing modifications, developments, and alterations in the structure of information; thereby he is designing the generative model of design. In this way, the computational thinking and its universality in representing almost any rule-based process is setting up the design process; and the creativity, insight, individuality of the architect is applying not only in the end product, but in the process as well. In other words, as a result of getting acquainted with the scripting/programming language, the architect is obligated to build the generative system of design with principles of computation. Thus, he begins to conceive computer programs and architectural design processes as glass-box models, which are transparent, flexible and clear systems.

In this context, it should be mentioned that computation and computerization are mainly confused in contemporary architectural practice. Computerization is just the concept of using computers in the production of final drawings of an end product, whereas computation focuses on the process of generating architectural products.[101] Computerized architecture is using computer as a "black-box" and a tool; the underlying structure of production is not essential. On the other hand, computational architecture perceives computers as an extension of mind: computation as a thinking mode deriving its models and computer domain as an

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[98] Philip Steadman. *Evolution of Designs: Biological Analogy in Architecture and the Applied Arts*. p.163.

[99] Kostas Terzidis. *Algorithmic Architecture*. p.xii.

[100] *Ibid*. p. xii.

[101] Ingeborg M. Rocker. "When Code Matters." *Programming Cultures: Art and Architecture in the Age of Software: Architectural Design.* Vol 76, No 4, 2006. p. 23.

interface. This approach is concerned in the logic of computational systems; the main interest is to examine and design the process. Similarly in this thesis, the cactus is reviewed through analyzing its underlying geometrical extensions and its generative mechanism instead of imitating a final form. In this manner, as soon as the generative algorithm of cactus organization is established, it turns out to be a 'motor diagram' that enlightens numerous different types and species of cactus.[102] Moreover, this motor diagram may unleash new possibilities that can emerge from the same generative mechanism but with minor changes in operations, variables or parameters.

A black-box mode of designing carries no deliberate information about the generative system of design. For the design process to get closer to a glass-box model, its information flow structure needs be explained with its elements, operations, and relations in a definite, explicit, and consistent manner. In the case of computer usage in architectural practice; when computers are perceived as black box devices, the architect is solely the executer of an already constructed model. He is limited within the drawn boundaries of the program and consequently he has inadequate control on the design process and the product. Since the generative model and its components are out of scope, there is no possibility of modifying it so that it would lead towards a better solution through advancing the model structure and reconsidering the assemblage of its components. Thus the computer program(mer) rather than the architect is the one, that is implicitly more decisive and effective on the design. On the other hand, in a glass-box mode of designing the generative system is well defined and transparent. Moreover, the emerging product is comprehended as an extension of the process. When the architect approaches the computer with such an insight, it becomes an interface where he is designing the design process. Therefore, for him the computer has the capacity of being flexible, variable and multifold in reference to the diverse processes it can model and the possibilities it can generate. In this case, the architect is the modeler and the model executer at the same time. This affiliation between the architect and model enables learning as long as the search towards a better solution continues.

In architectural explorations, learning is essential in the search for a better solution. In a black-box perception of the computer, when the output is found inadequate to satisfy the requirements, the architectural research can be continued through changing two variables: the input and the command. The possible moves are either to define a new input with the same command or the same input with another executed command. Since the nested

[102] Motor Diagram is defined by: Manuel DeLanda. "Delueze and the Use of the Genetic Algorithm in Architecture." in *Phylogenesis: foa's ark*. Edited by Foreign Office Architects. Barcelona: Actar, 2004.

operations are not visible in a black box perception, the architect is following a 'trial and error' procedure. Either arbitrarily or intuitively, by assigning inputs/variables the architect tries to establish a superior and satisfycing outcome. Consequently, this activity can be evaluated as an unconscious manner of practicing computation and design. For example, when a triangle is drawn through the Rhinoceros Modeling Program within a black-box procedure, the triangle is defined with three parameters: the center of the equilateral triangle, the length of one edge and the orientation of one corner.(Figure 3.2) However, the constructive underlying geometry of the triangle is not visible and comprehendible to the user. In this manner, it is not possible to designate an elaborated associative geometry that the triangle will be a part of or will emerge beyond itself.

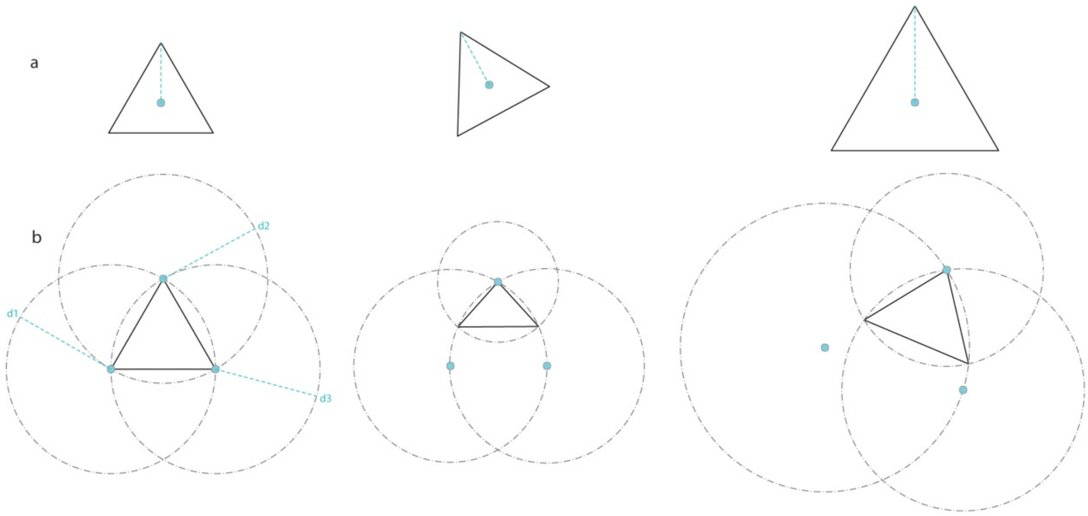

Figure 3.2 Black-box(a) and glass-box(b) modeling of triangles in Rhinoceros 3D Modeling Program. [Drawn by the author]

On the contrary, in glass-box insight of computer usage in architecture, the progress towards a better solution happens through learning and feedback loops. The interrelated information processing structure, which includes the inputs, nested commands, relations, dependencies, constraints, variables, and parameters, is transparent. Whenever a superior solution is searched, it is possible to ascertain on-point modifications such as changing the dependency graph, the values of parameters, or defining new constraints. Herbert Simon names this approach for developing the glass-box generative system as the 'generate-test cycle'.[103] In a global generate-test cycle of computational modeling, other nested series of test cycles and nested feedback loops that thrive learning take place. By this multi-layered structure, the

[103] Herbert A. Simon. *The Sciences of the Artificial*. Third Edition. Cambridge, MA: The MIT Press, 1996. First published in 1968. p. 74.

architect gains control and consciousness on the generative agents of the outcome. In the case of triangle drawing, the glass-box understanding of the geometry is defined by as many parameters as the user wants or needs. A glass-box model includes the geometrical foundations and derivations of the triangle, a system of its emergence.(Figure 3.2) In this manner, a vast number of possibilities can be researched within the alteration range of the parameters. Moreover, the user is consciously designing; and he/she is profoundly taking advantage of the computing and simulating intelligence of the program.

Therefore in design methods studies, glass-box is considered as the opposite of black-box understandings of design process. In a computational glass-box process, the architect can distinguish which parameters or variables are more effective or which dependencies and relations need to be established to improve the outcome. Furthermore, in a glass-box design process, learning is a means of elaborating the generative system in order to obtain more precise, coherent and fitting solutions. Besides, the erudite information about the process may be inherited for future inquiries on another similar architectural form generation model. From this perspective, when natural organizations and phenomena are clarified as glass-box models, they turn out to be instructors about systems and information processing structures. A glass-box understanding of natural phenomenon reveals a complex dynamic model, which changes, modifies, evolves, and adapts while it searches for a better solution to satisfy a specific purpose or goal. [104] Furthermore, a glass-box systematization of nature can open up new horizons for architectural design as it instructs information flow schemas, part-whole associations, and inter-woven dependencies between parameters, variables and outcome.

In the cactus studies, which are illustrated in detail in the following chapters of this thesis, it is intended to analyze, interpret and construct the emergence of cactus form as a glass-box model. Thus in this model, it is possible to observe the agents deriving the form in relation to the water collecting, self-shadowing and self-conditioning performance of the cactus. It shall be noted that there is a dynamic correlation and critical tension between the parameters, variables, external forces, environmental conditions and genetic generative operations, which altogether will end up with an equilibrium under satisfycing circumstances. The aimed transcoded knowledge fundamentally is this dynamic system where form and performance are both effective and determinant on each other and on the global outcome.

To sum up, comprehending computation as a mode of thinking and an interface enables constructing glass-box models deriving the design process. Furthermore, the "mindset" that

[104]Philip Steadman. *Evolution of Designs: Biological Analogy in Architecture and the Applied Arts*. pp. 164-167.

computational thinking and its tools offer, should result in a “mind shift” in architecture: another mode of analyzing, interpreting, and applying relevant information.[105] Hence, within this new “mindset” architecture reevaluates its environment and its connections to other disciplines. Through computation, architectural design can surmount the difficulties in constructing complex and integrated systems wherein various kinds of data from several disciplines are embedded as inputs, which are effective on the global outcome.

In this perspective, since natural phenomena embrace complex and dynamic generative systems, comprehending them as glass-box process and uncovering the underlying orders, rules and principles is essential for learning about system behavior. The “mindshift” and “mindset” that computation triggers promote the practice of revisiting natural phenomena in terms of its processes. Afterwards, this process model acquired from nature can be re-evaluated in terms of their implications and applications in architectural design processes. The consistent, dynamic, associative, and integrated character of natural systems, thus, will be the intelligence to transcode from nature to architecture. In the case study, cacti are analyzed within such an eager to re-look and re-understand the emergence of cactus form in a computational mindset. The intelligence of the cactus is considered as the system of its formation of waterways, their behavior under fluid dynamics, its areole formation, and their self-shadowing behavior under sunlight. In other words, the reciprocal work between form and performance is selected as the knowledge to transcode from cacti to architecture.

3.2. Modeling and Mapping: Systematizing and Restructuring Reality

The universe is consisted of various kinds of information; this information is set differently each time human mind intends to define it as a system under a theory. Therefore, the model of a natural or artificial organization may have different configurations according to the analyzing, learning, thinking modes of the individual. Each mode of thinking generates a legitimate model of the existing data; in other words each “mindset” derives a new setting of the universe.[106] At this point of defining the “mindset”, the inner logic of computers turned

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[105]Arzu Gönenç Sorguç, “Bilgisayarak Öğrenmek, Bilgisayarla Öğrenmek.” *16. Sosyal Psikiyatri Kongresi*, Safranbolu, 4-8 July 2009.

[106] “Mindset” and “minshift” terms are borrowed from:

Ibid.

Arzu Gönenç Sorguç, Semra Arslan, “Art and Literature as a Teaching/Learning Interface of Mathematics for Students of Architecture”, *ECAADE 2009*, Istanbul, September 2009.

into a guide more than a tool in terms of their algorithmic processes and their reflections/contributions in human reasoning. John H. Holland explains:

> "Although model building is not usually considered critical in the construction of scientific theory, I would claim that it is. Every time a scientist constructs a set of equations to describe the world, such as Newton's or Maxwell's equations, he or she is constructing a model. Each model concentrates on describing a selected aspect of the world, setting aside other aspects as incidental. If the model is well conceived, it makes possible prediction and planning and it reveals new possibilities."[107]

Building structured descriptions, of mental constructions, natural and artificial phenomena with a level of abstraction and detail, is called modeling. Models are structural representations of an idea or reality that is a means of thinking, comprehending, interpreting, communicating and making future projections. In the dictionary, model is defined as "a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions ".[108] Mathematics, as an example of modeling literacy, presents a structure that can conjure up systems with various relations and operations to build models in order to explain the behavior of real devices, objects and phenomena. [109] Charles Rickart emphasizes the essential role of structures and systems in thinking, through which human brain manages information and knowledge. He asserts the general assumption behind this thought as "that information is coded and stored in the brain in the form of structures; and that brain is especially designed for recoding and processing these structures."[110] Rickart's interpretation of coded information is also embedded in modeling, since all models are comprised of a certain structure that configures data, information flow, and relations within a specific literacy and symbolic language. Hence, each model has its own function/interest and character: a framework, which sets up the data inherited, and an operative system, which includes rules, symbols and pattern of relations.

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107 John H. Holland. *Emergence: From Chaos to Order*. New York: Oxford, 2000. p. 4.

108 *Oxford dictionaries Online*. Available from: http://oxforddictionaries.com/ Last resumed at 05.04.2011.

109 Clive L. Dym. *Principles of Mathematical Modeling*. Amsterdam ; Boston : Elsevier Academic Press, 2004. p. 4.

Also Rickart argues that humans use structures for building various systems:
Charles Rickart. "Structuralism and Mathematical Thinking." Chapter in *The Nature of Mathematical Thinking* edited by Robert J. Sternberg, Tali Ben-Zeev. Mahwah, NJ: Lawrence Erlbaum Associates, 1996. pp. 285-300.

110 Charles Rickart. "Structuralism and Mathematical Thinking." Chapter in *The Nature of Mathematical Thinking* edited by Robert J. Sternberg, Tali Ben-Zeev. Mahwah, NJ: Lawrence Erlbaum Associates, 1996. p. 285.

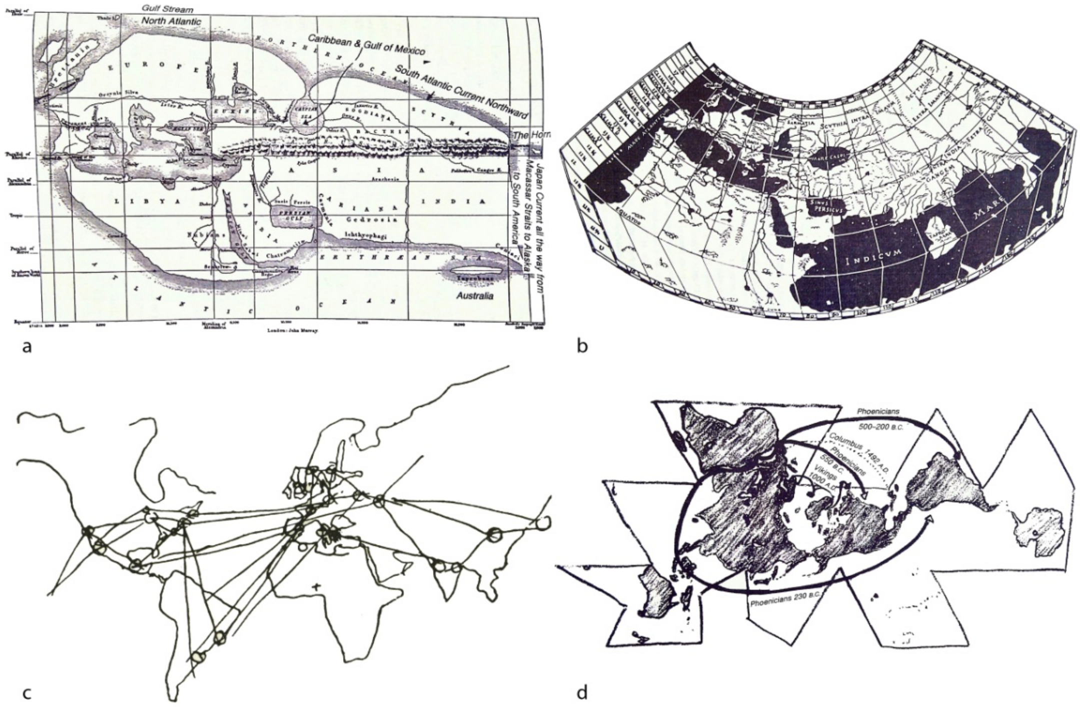

Figure 3.3 The evolution of world maps, with different levels of precision, different constructive systems, and different kind of information. (a) Eratosthenes' Map (200 B.C), (b) Ptolemy Map (200 B.C.), (c) Le Corbusier's world map, (d) Buckminster Fuller's Dymaxion Map showing early circumnavigations.

Figures (a), (b), and (d): Buckminster Fuller. *Critical Path*. pp. 36, 42, 45.

Figure (c): Le Corbusier. *The Modulor : A Harmonious Measure to the Human Scale, Universally Applicable to Architecture and Mechanics*. p. 126.

Correspondingly, the activity of -mapping- is a mode of modeling using visual media and literacy. It can vary in *function, information, visual vocabulary,* and *grammar*.[111] Common to all mapping processes, functions are deriving operations, through which the intended data extracted from reality is translated to the target map language (symbols, graphics, etc.). Maps may appeal to different functions regarding the information it intends to include/transmit, and the subject area or discipline it intends to serve. They may use different visual syntactic rule sets and graphic constructions in order to rewrite the committed information in totality and consistency. In other words, in a modeling/mapping practice there exists a reference system and a constructive system; they regulate what will be the knowledge domain that the model will serve or target, and how the reality will be depicted and translated. The reference

[111] Tomas Subrt, Helena Brozova. "Knowledge Maps and Mathematical Modeling." *The Electronic Journal of Knowledge Management*. Vol 5, Issue 4. pp. 497-504. Available online at www.ejkm.com. Last resumed at 11.09.2011.

system and the constructive mechanism propose and support each other to establish a complete and consistent map.

The reference system and the constructive mechanism directly influence the inherited information and precision of a map. It can be observed from several world maps that: as the reference system and constructive mechanism becomes more complex and well defined, the topographical properties and the spherical topology of the Earth gets more precisely represented.(Figure 3.3) In addition to that, the specific aim of a map can also determine which type of information will be represented more precisely and in detail and which will be eliminated or abstracted. Naval maps are familiar examples that exhibit the mentioned properties of mapping like data translation, visual language construction, and being context specific. Naval maps aim to serve to navigational usage for sea captains. They include required information for navigation in the sea and they are build in a universal visual language which is able to represent seawater depth, detailed border lines of land, marinas, country frontiers at the sea, etc. A zoologist, investigating fish species in the same section of the sea, may not find fundamental information about his subject of study through this map and he may not be even using this map for his navigation as effective as a sailor. Thus, the driving forces of mapping are the *intended audience* that the map is going to appeal, and the *system* that will determine how information is going to be translated in order to represent the specific data from reality with a level of abstraction.

It shall be noted that mapping refers to more than just developing world maps or reconstructing physical reality. Mental structures such as knowledge and thinking, or abstract concepts such as social, psychological, cultural values, or processes such as workflow and collaboration can also be mapped. Thus, systematic reconstruction of processes, sequences and relations are also subject to the diagrammatic compositions of mapping. Knowledge maps, information flow schemas, and mind maps are just a few to exemplify the multiplicity of mapping domain. In fact, it can be interpreted that the transcoding of cactus as well includes an embedded mapping practice. Understanding the formation process of cacti necessities a mapping of information flow, relations and dependencies between the parameters, variables, operations and the outcome. This mapping is oriented by the individual interpretation of the modeler, the knowledge that is intended to extract, the theoretical construct and the modeling literacy – the representative medium and language.

In this thesis, the modeler is concerned to obtain information about the association of form and performance of cactus species through common computational algorithms and relations. For instance, the water channels existing in the cactus body is associated with the areole configuration, which are parameterized jointly by a specified angle of rotation and level difference between each polygonal layer.(Figure 3.4) Thus, this mapping of local-global interactions can generate the total outcome by solely ascertaining some initials. A change in the specified rotation angle between layers will end up with a different areole configuration and global form, new water collecting paths and diversified performance of fluid dynamics. Correspondingly, the architectural inferences of such a process will be illuminated, as it will depart from being a formal analogy towards establishing similitude of behavior. In short, mapping is an integral process in transcoding a dynamic natural system into architectural design.

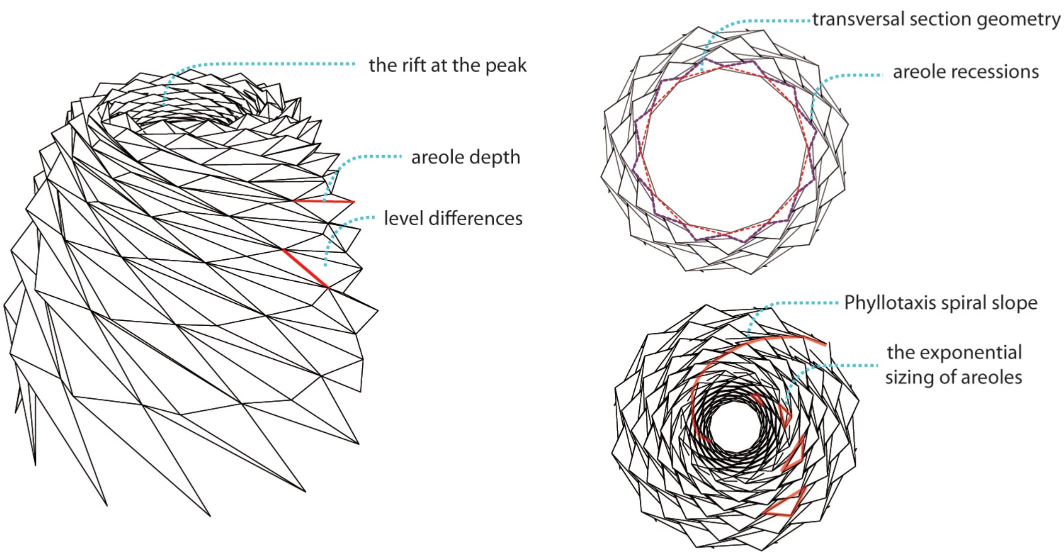

Figure 3.4 The detection of associated cactus geometry for mapping the cactus properties in the transcoding model. [Drawings by the author]

3.2.1. The Significant Role of Literacy and Mode of Representation in Modeling

Models are representations of reality; through the translation of reality into an abstract setup, language and syntax of the model are one of the most effective determinants on what type of information can be embodied, and how this information is going to be constructed as knowledge. It should be noticed that world maps wouldn't be depicted properly and user-friendly, if the information were explained by written language and verbal system, or algebra and mathematical formulas instead of graphic representations. In the process of modeling, the particular behavior or feature of the phenomena that will be systematized settles the constructive system, which determines the set of rules, principles, methods, techniques and organization schema. In other words, the constructive *system* characterizes the model and how the model will structure data assembly by establishing the way of thinking, information flow, inscription language, syntax and vocabulary.[112]

Human use of representations in thinking is a major topic to discuss when modeling is in the focus. The mode of representation (descriptive system) and the mode of thinking (theoretical framework) are correspondingly promoting and influencing each other for building models of the reality. Theory reconfigures, certifies and advances the media of representation depending on the requirements for knowledge construction. And vice versa, representation is the major determinant in the process of data assemblage and knowledge construction. Herbert Simon, who proposed a curriculum for a new theory of design based on sciences of the artificial, declared the importance of representation in design-centered studies:

> "…I have said little about the influence of problem representation on design. Although the importance of the question is recognized today, we are still far from a systematic theory of the subject- in particular, a **theory** that would tell us how to generate effective problem representations."[113]

Simon has pointed out the significant impact of representation bond to theoretical construction. In other words, it can be argued if he calls out the necessity of a model, which results from the association of theory and representation. Moreover, the model Simon demands for has the capability of representing the design problem that can be interpreted as the design process. Design is a complex and multi dimensional process that takes inputs from the social, material, abstract realms. Therefore, a representative language that can cover various types of information within a common structure and in a single global system is critical. Nevertheless, computation propounds a structure and literacy that can potentially fulfill the deficiencies in representing and operating design as a total complete system.

The role of representation and media in the process of building mental constructs is identified with the term '*literacy*'. Since the term derivates from 'literate' and 'literature', basically literacy refers to the ability of reading and writing.[114] Now, since there has been a multiplicity of descriptive systems for communicating ideas and constructing knowledge, the term 'literacy' is used for elucidating the consolidation of thinking and conceiving ability of men through representation. Salomon marks out literacy as "one's ability to extract information from coded messages and to express ideas, feelings, and thoughts through them

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[112]Andrea DiSessa. *Changing Minds: Computers, Learning, and Literacy.* Cambridge: MIT Press, 2001.

[113] Herbert A. Simon. *The Sciences of the Artificial*.(1996) pp. 132-133.

[114] *Merriam-Webster Online Dictionary.* Available from: http://www.merriam-webster.com/ last resumed in 13.08.2011.

in accepted ways; the mastery of specific mental skills that become cultivated as a response to the specific functional demands of a symbol system"[115] Thus, literacy has been recognized as the advance of men's abilities such as comprehending, analyzing, describing and creating meanings within a descriptive system. In other words, literacy acts as the process of practicing an instrumental medium for the person in order to build up ideas and to communicate these ideas with herself/himself and others and to communicate with his surroundings.[116]

Developments in information technology and multimedia introduced diverse modes and media of communication- thus different sorts of literacy.[117] The common usage of televisions, computers, Internet, and personal touch pad computers has been changing extensively the mode of observing, learning, thinking, and expressing oneself. In parallel with this change, literacy gained a broader meaning, as the new sorts such as *media literacy, visual literacy, multiliteracies, technological literacy*, and *representational literacy* got defined as some of its subtitles.[118]

Nevertheless in this thesis, literacy will be grouped under five main titles: verbal, visual, artisanal, mathematical, and computational. Verbal literacy refers to linguistic communication and concerns with written language, vocabulary, syntax, and semantics. Dissimilarly, visual literacy includes pictorial, graphical, diagrammatic, or material system of representations and it can be illustrated as technical drawings, flow charts, pictures, or scale models. In addition to these, artisanal literacy implies accumulation of knowledge through labor and experience.[119] On the other hand numbers, functions, mathematical notions, and formulas consist the symbolic system of mathematical literacy. These different

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[115] G. Salomon quoted in Pamela H. Smith. *The Body of the Artisan: Art and Experience in the Scientific Revolution.* Chicago: University Of Chicago Press: 2006.
Original quote is in G. Salomon. "Television Literacy vs. Literacy, " Journal of Visual / Verbal Languaging, vol 2, Fall 1982. p. 7.

[116]Andrea DiSessa. *Changing Minds: Computers, Learning, and Literacy.* Cambridge: MIT Press, 2001.

[117] Robert Ferguson. "Democracy and Media Literacy," Foreword in *Democracy, Multimedia Literacy and Classroom Practice: A European Experience*. Edited by Alfonso Gutiérrez Martín and Armin Hottmann. Berlin: Mondial Verlag, 2002. pp. 7-17. His keynote speech given at Berlin Media Literacy Conference 29th June 2002 at the Open Channel Berlin.
Available from: http://www.23muskeltiere.de/europe/download/DemoMultiClass.pdf last resumed at 13.08.2011.

[118] David Reinking. "*Literacy - Multimedia Literacy*". Available from: http://education.stateuniversity.com/pages/2186/Literacy-MULTIMEDIA-LITERACY.html
Last resumed at 13.08.2011.

[119] Pamela H. Smith. *The Body of the Artisan: Art and Experience in the Scientific Revolution.* p. 8.

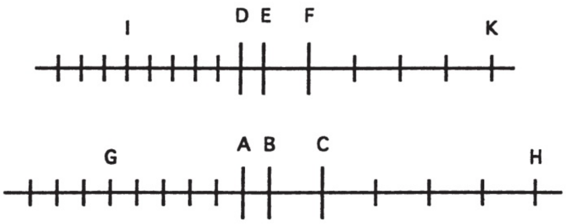
sorts of literacy have distinct principles that are effective in the process of structuring data. For example in verbal system, the arrangement and ordering of words cause alterations in the meaning and emphasis of the sentence. Besides in mathematical sentences, rearranging and reordering a settled formula don't make difference in the general connotation, but it leads to derivative equations.

a

If a moving particle, carried uniformly at a constant speed, traverses two distances the time-intervals required are to each other in the ratio of these distances.

Let a particle move uniformly with constant speed through two distances AB, BC, and let the time required to traverse AB be represented by DE; the time required to traverse BC, by EF; then I say that the distance AB is to the distance BC as the time DE is to the time EF.

Let the distances and times be extended on both sides towards G, H and I, K; let AG be divided into any number whatever of spaces each equal to AB, and in like manner lay off in DI exactly the same number of time-intervals each equal to DE. Again lay off in CH any number whatever of distances each equal to BC; and in FK exactly the same number of time-intervals each equal to EF; then will the distance BG and the time EI be equal and arbitrary multiples of the distance BA and the time ED; and likewise the distance HB and the time KE are equal and arbitrary multiples of the distance CB and the time FE.



And since DE is the time required to traverse AB, the whole time EI will be required for the whole distance BG, and when the motion is uniform there will be in EI as many time-intervals each equal to DE as there are distances in BG each equal to BA; and likewise it follows that KE represents the time required to traverse HB.

Since, however, the motion is uniform, it follows that if the distance GB is equal to the distance BH, then must also the time IE be equal to the time EK; and if GB is greater than BH, then also IE will be greater than EK; and if less, less. There are then four quantities, the first AB, the second BC, the third DE, and the fourth EF; the time IE and the distance GB are arbitrary multiples of the first and the third, namely of the distance AB and the time DE.

But it has been proved that both of these latter quantities are either equal to, greater than, or less than the time EK and the space BH, which are arbitrary multiples of the second and the fourth. Therefore, the first is to the second, namely the distance AB is to the distance BC, as the third is to the fourth, namely the time DE is to the time EF.
Q.E.D.

(From Galileo, Dialogues Concerning Two New Sciences. Translated by H. Crew and A. de Salvio [Northwestern University, 1939], pp. 155–156.)

b

$$d_1 = r_1 t_1$$
$$d_2 = r_2 t_2$$
$$\downarrow$$
$$\frac{d_1}{d_2} = \frac{r_1}{r_2}\frac{t_1}{t_2}$$

Figure 3.5 (a) Galileo's verbal explanation for the theorem of uniform motion with constant speed, (b) the mathematical notation that the theorem refers in algebra.

Andrea DiSessa. *Changing Minds: Computers, Learning, and Literacy.*

Moreover, the representative system deeply influences the process of comprehending information, processing the data, and making progress. The descriptive system shall describe the intended phenomena in a clear, simple, and neat way such that the idea or the problem becomes transparent.[120] Therefore, every systematized descriptive system elaborates properly

[120] Herbert A. Simon. *The Sciences of the Artificial*.(1996) p. 132.

a particular kind of information. For example, a long paragraph and one line of arithmetic equation can express the same kind of information. Galileo's struggle for describing scientific theorems with verbal language fits to exemplify this statement. Galileo, as a physicist, mathematician, astronomer and philosopher of 16th and 17th century, had explained his theorem of uniform motion with a constant speed in verbal literacy of written language.[121](Figure 3.5) If Galileo was introduced to the thinking system and tools of modern algebra, which did not exist until 50 years later, he may have built his theorems structured in mathematical literacy.

Algebra is a better fit than literature for the purpose of depicting Galileo's theorem because it enables usage of equations and offers the possibility for basic manipulations.[122] The mathematically modeled theorem of Galileo, defines uniform motion under constant speed leading to proper comprehension of the idea, and allowing for further interpretations, modifications, developments. Thus, the projected data that the model will transmit and the descriptive language that will build the model are closely interrelated. Representing data of the "real world" in the "conceptual world" through mathematics includes three phases: observation, modeling, and prediction.[123] Thus, mathematical models provide clear, simple, and open to manipulation reconstructions of the observed phenomena and behavior. Depending on the subject of modeling, the determined modeling literacy manifests its potentials and limits in depicting such a knowledge domain. Mathematical models are satisfying and qualified for developing most theorems in physics or chemistry. Yet, weather forecasting, for instance, necessities another modeling literacy, which can construct a more complex, and dynamic information flow system. Such dynamic systems possess a vast amount of variables and parameters; and they require long arithmetic calculations within a limited processing time. Dissimilar to written language and calculus, computation enables the phenomena of weather to be modeled within a global integrated and associated system that can still be easily editable and rapidly executed.

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[121] Andrea DiSessa. *Changing Minds: Computers, Learning, and Literacy.*

[122] Ibid.

[123] Clive L. Dym. *Principles of Mathematical Modeling*. Amsterdam ; Boston : Elsevier Academic Press, 2004. p. 4.

3.2.2. Computer Literacy and Computational Models

Representing systems in computational notations and through computational principles is closely bounded with and derives from a mathematical setup; yet computational and mathematical models stay dissimilar in various aspects. The spiral growth in nature and its mathematical models, which have been modeled through history under different names and topics, can illustrate a part of these diversifying aspects. Computation and computational thinking presents a computational literacy that uses symbols, algorithmic relations, and constructive logic: principles that don't fall apart from mathematics and mathematical thinking. As the 'grammar' and 'vocabulary' to define reality are defined by computational medium, the way we see, understand, systematize, and model the world's entities has changed comprehensively, creating a "mind shift".

Computational models explain the emergence and behavior of a phenomenon through systematizing its generative variables and parameters, and through structuring the dependency of these determinants with each other. Consequently, it is possible to define any system -simple or complex- with a set of initial inputs/elements, rules/ laws/ operations, constraints/ variables/ parameters, and an information-processing schema.[124] John H. Holland states, "A small number of rules or laws can generate systems of surprising complexity." [125] The complexity of a computational model doesn't derive from the intricacy of its lower elements or local operations, but from the well-established relations between these elements and operations. In a computational setup, the information flow schema braces up the system. Holland puts forth the notion of 'perpetual novelty' to characterize the potential complexity of a system, where the information flow is ascertained by numerous multi-dimensional operations, relations and dependencies.[126] The possible alterations in the generative process and information flow through time and after generations do also support the enrichment of the perpetual novelty. Hence, as the process gets more dynamic, the outcome happens to be more unprecedented, and thus the perpetual novelty of the model increases.

Computational models and processes hold the potential for acquiring high perpetual novelty. Manuel DeLanda, after Deleuze, specifies the multitude of 'the space of possible states',

[124] Stephan Wolfram argues that any system can be defined and explained by computation: Stephan Wolfram. *The New Kind of Science.* Canada: Wolfram Media, 2002.

[125] John H. Holland. *Emergence: From Chaos to Order*. pp. 3-4.

[126] Ibid. pp. 3-4.

which can refer to the set of possible outcomes rising from a single model.[127] Holland's assessment of 'perpetual novelty' and DeLanda's appraisal for 'the space of possible states' have the common approach in evaluating a model: the dynamic behavior of the model and the multiplicity of its possible outcomes make the generative system more productive and unprecedented. Dynamic and complex computational models can be exemplified with contemporary weather forecasting. Computer aided weather forecasting is the systematic construction of parameters and variables by computational tools/operations and in algorithmic information flow possibilities.[128] Computational weather models are revealing the parameter-based infrastructure of weather condition alterations. Accordingly, computational weather models refer to complete systems where numerous parameters and variables are embedded and related in the global system, such that a minor alteration in one input can change the outcome extensively. In short, one model can conjure up numerous outcomes and products; and this character constitutes the perpetual novelty of computational weather models.

Once the parameters and their linkage are set in the computational model, future projections about alterations in weather conditions can be obtained through observing changes in these parameters and redefining their values. However, modeling is not about building an explanation that will merely enlighten a phenomenon at a frozen time interval. Instead, modeling is about constructing a universal system and logic that will include explanations and definitions for all possible behaviors of the concerned phenomenon. Computational models provide doing several trials of a system with different variables in a short time; because of their editable parameter-based algorithmic structure, their rapid processing time and their ability to process complex, multivariate systems. In this sense, computational models differ from others in reference their advantageous, editable, precise, and flexible structure.

Holland emphasizes the dissimilarity of computational models from other descriptive models belonging to distinct literacies as such:

> "Computer-based models present the modeler with a rigorous challenge. The claims of verbally described models are often established by rhetoric.[…] The same can sometimes be said of traditional mathematical models, where even the most rigorous mathematical proofs skip "obvious" steps. It is impossible to skip steps in a computer program. The computer executes each and every instruction in the sequence given... Similarly, a computer-based

[127] Manuel De Landa. *Intensive Science and Virtual Philosophy.* London: Continuum, 2002.

[128] John H. Holland. *Emergence: From Chaos to Order*.

> model is both *rigorously described* – presented as a program that can be examined in detail – and it is *executable*."[129]

For a computational model to work accurately, the generative process, the initials and rules need to be complete, consistent, and well-defined. And vice versa, every generative system, which is processed through definite rules and operations, can be modeled by computational thinking and computational media.

The capacity to describe various types of phenomena with computational principles makes distinct disciplines develop their discourse on a common theoretical ground. [130] Computation has been an interface for information exchange between different subject areas. Accordingly, through computation the boundaries between disciplines become indistinct. The ongoing collaborative research environment between architecture and biology is a result of such progress. Constructing computational models of natural phenomena clarifies the information processing schema and generative system of the related object, device, or organization with simple rules and initials. In this manner, it becomes possible to transfer the rule-based knowledge of form generation from the natural domain to the architectural. Within such collaboration between biology and architecture, the observed biological phenomenon turns into a source for learning about data management and generative processes in architectural design.

The information exchange between disciplines is developed through establishing affinities (analogy or similitude) between distinct organizations. And models can serve to comprehend the common behavior of distinct organizations by uncovering their global generative system, and the relations and dependencies between system elements. Through a level of abstraction, a model intends to highlight a kind of information that is common in the investigated entities. As a frequently used object of affinity, trees have been modeled in order to highlight the branching information flow structures belonging to natural and artificial systems, which include hierarchical organizations such as blood vessels of human body, family pedigree or kinship of animal species. They all have been illustrated with branching configurations, analogous to trees. Digital drawings and renders of a tree remain descriptive and representative. Moreover, a computational model of a tree depicts the generative system of growth. Therefore, within such a model, various outcomes can be obtained by altering the values of parameters. A model of a tree can also produce a snowflake, if the direction of branching growth is introduced as a variable. In such a model, a directional growth from an

[129] *Ibid*. p. 17.

[130] Herbert A. Simon. *The Sciences of the Artificial*. (1996) p 137.

origin point will emerge a tree, whereas a uniform growth towards all directions from a center point will emerge a snowflake. Without doubt, the snowflake could be obtained as a result of another computational model. To name one, a fractal system with replacement method could also produce a snowflake.

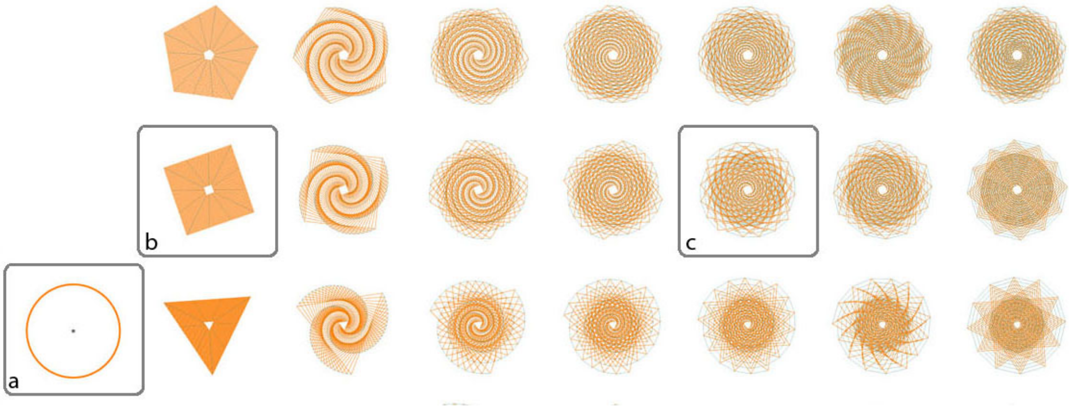

Figure 3.6 A set of possible outcomes deriving from the computational model that is constructed by interpreting the Mayan Pyramid's top view. [Scripted and illustrated by the author]

Rows change depending on the polygonal vertex number, and columns change depending on the rotation angle between scaled steps. (a) The user-defined core geometry of the generative system, (b) one of the generations corresponding with the Mayan Pyramid, (c) one of the generations resembling the top view of a cactus.

However, common to all models of trees systematized through different configurations, they have reduced the complexity of trees at a level of simplification so that the model inherits/includes the adequate knowledge serving the analogy/similitude without leading to confusions or misunderstandings. Furthermore, computational model of a tree is different from the solely geometrical, mathematical, visual or metabolical. A computational model of a tree may embrace them all as a whole, since it defines a tree by its rules of growth depending on interconnections and operations between various parameters and variables. It includes mathematical equations using adjustable variables, so that the model will generate a tree system, which in turn may not look like a tree but a fractal snowflake. Equally, a Mayan Pyramid model, which is defined through algorithmic operations and computational principles, may generate outcomes that correspond with the phyllotaxis of a specific cactus type.(Figure 3.6) That is to say, computational thinking, structures, and models enable comprehending two or more distinct organizations as different possible states of the same generative system. Moreover, computational thinking facilitates an understanding that a natural or artificial organization may refer to more than one generative model. Accordingly, the cactus model studied in this thesis, should be acknowledged as just an interpretation of cacti organizations. Numerous computational models could have been established that would vary in detail and abstraction, parameters and variables, level of complexity and completeness, and in the structure of generative algorithm.

Through modeling natural or artificial organizations, generative processes of their 'becoming' shall be considered as crucial. In this way, their model may serve as an interface that instructs processes of 'becoming's for generating other artificial organizations. Thus, similitude, which refers to similarity of behavior between two distinct organizations, is more possible to be achieved and controlled. By 'becoming', Detlef Mertins denotes the process of 'building'/establishing, and the property of being 'unformed'/in-progress.[131] In his article named "Architectures of Becoming: Mies van der Rohe and the Avant-Garde", Mertins argues that 'becoming' was also a main issue to discuss in the modernist discourse throughout the settlement of the emerging new architecture. This is not surprising though, when we consider that the main philosophy of the era was positivism and there was a common reliance on the idea that complex systems are composed of simple initials.[132]

In this thesis, 'becoming' is acknowledged as the process of generation common to both architectural and natural organizations, and the process of building the model – composing a system of algorithmic principles in a computational model. Therefore, two implications of 'becoming' have been introduced: the morphogenetic process of the cactus and the possible architectural products, and the construction process of the model. In this sense, Mertins implications from 'becoming' as the process of 'unformed' and 'building' are sustained. Moreover, the contemporary inquiries towards a more integrated association of architecture and computation can be deciphered as another process of 'becoming' in the global outlook. Hence, 'becoming's of an organization or constitution are essential for understanding the phenomenon expansively.

Similarly, Deleuze emphasizes the significant role of generative processes in comprehending a phenomenon profoundly. According to Manuel DeLanda's readings of Deleuze, natural

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[131] Detlef Mertins. "The Architectures of Becoming: Mies van der Rohe and the Avant-Garde." *Mies in Berlin*.

Detlef Mertins refers to becoming as "building" at page 107 and as "unformed" at page 110.

[132] Peter Gallison. "Aufbau/Bauhaus: Logical Positivism and Architectural Modernism." In *Critical Inquiry*, n. 16, 1990. pp. 709-752.

Abbott J. Miller. "Elementary School." *The ABC's of [Yellow Triangle, Red Square, Blue Circle]: The Bauhaus and Design Theory*. Edited by Ellen Lupton and Abbot J. Miller. New York: The Cooper Union for the Advancement of Science and Art, 1993.

entities shall be defined in terms of their 'morphogenetic processes'.[133] Morphogenetic processes can be said to possess a level of perpetual novelty. In order to explain the variety and similitude rising from alterations in morphogenetic processes, DeLanda defines the concepts of 'multiplicity' and 'manifold' as "*the structure of spaces of possibilities*" and "*the space of possible states*".[134]

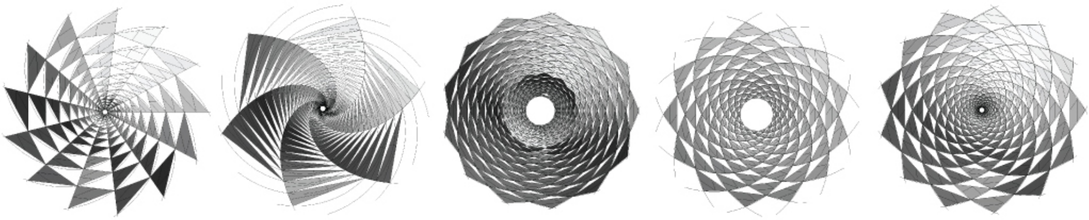

Figure 3.7 A collection of possible states generated from the Cactus Script with different user defined inputs. [Renders established from the Cactus Script that is developed by the author]

Consequently, an identical generative processing structure can rise up a vast amount of distinct outputs as result of the adjustments in its parameters. For instance, a computational model of the cactus defines the initials, variables, parameters, relations and parameters and how they are configured in a specific structure, concludes to a defined space of possible states.(A selection is shown in Figure 3.7) This model is a simplified system interpreting the generation and growth of cactus. It gets more complicated to depict or illustrate in a graph, while its structure gets more complex as the variables and relations are defined and linked further more. The model, then, identifies *the structure of spaces of possibilities*, while the probable outcomes of the model constitute *the space of possible states*. Thus, once the structure of the process is set, an extensive set of possibilities concerning architectural design, innovative engineering, sustainable solutions can be derived from the cactus. In the cactus studies, it has been observed that the spiral phyllotaxis and growth of the cactus is common in most of the cactus species; and yet it is varying in numerous aspects such as the amount, curvature radius and rotation angle, growth factor and size. For this reason, it has been purposed to be systematize mainly the spiral configuration of areoles and the performance of these spirals within the scope of this thesis. The parameters, variables, and relations have been assigned to the computational model such that the outcomes can pair up

[133] Manuel De Landa. *Intensive Science & Virtual Philosophy*. p. 9.

[134] Ibid. pp 9-13.

with different cactus species. In other words, *the structure of spaces of possibilities* has been designed in such a manner that *the space of possible states* would include various types of cactus.

Computation, then, turns out to be a common ground to explain and compare two distinct devices, organizations, or phenomena in terms of their 'becoming', in other words generative processes. The case study on cactus and architecture, which is covered in this thesis, illustrates this aspect of transcoding in detail in Chapter 4 and 5. The associated becoming of cactus form and performance is parameterized in a computational model such that its implications for architectural products are studied for obtaining a common ground for high-rise buildings, built terrains, and double façades. In this way, computation turns to be a field of inquiry and interface, as generative computational models of nature become the key source of learning for architectural design. Therefore, with the mode of thinking, method and medium of computation, knowledge of the complex natural processes is transcoded in the artificial, through establishing a similitude of behavior/system and multiplicity of products/outcome.

It shall be noted that a computational model embodies outcomes and results as well as the process. However, while the process is identified in a particular structure, the inputs and outcomes of the global system and local operations are enunciated in terms of their properties and character. In other words, in order to build a complete system, the model needs to enunciate the output of a computational operation, since it is going to be the input for the sequential operation. And for the sequential operation to work properly as a part of the global system, it is mandatory to set-up the characteristics of the input (output of the previous operation) responding to the requirements of the operation. For example in the cactus model, the system initiates from a polygonal horizontal section. By the operations of scaling, rotating and translating a copy of this section, the secondary section is placed. While this operation sequence is repeated in loops for each generated section, all the sections throughout the cactus body are generated. Therefore, in order to execute these local operations properly, the inputs, parameters and variables shall be enunciated: a polygonal polyline as the input, a number between 0-180 as the rotation angle, a fractional number signifying the scale factor, a vector in (x,y,z) notation as the translation difference, plus a coordinate in (x,y,z) notation for a reference point that this vector is going to apply to. Hence, even if an exact number or value is not given, the domain of the possible numbers and values have been pre-indicated. Similarly as the outputs of an operation become the inputs of the next, the character of an output needs to be set-up beforehand as well for the global system to work without tumbling.

3.3. The Role and Virtue of Computation in Knowledge Exchange between Architecture and Nature

3.3.1. Computer as a Meta-Interface embracing sub-interfaces for modeling

In natural sciences, knowledge constitution is at the melting point of theoretical constructions and factual novelties. Through observing and analyzing natural phenomena, natural sciences discover and uncover the simplicity behind their complexity coat.[135] In this practice; theory, which comprises the mode of thinking and technique for practicing, configures the mental, mathematical and systematical constructs that direct the scientific research. Thus, theory draws the framework, which designates the scientist's interactions and approaches with the observed object of interest. Hence, theory presents patterns and models that shape the convergence of the scientist with a phenomenon from reality.

For instance, a contemporary scientist, who studies constructing models of meteorological phenomena, starts his studies by deciding the perspective and thus the boundaries of the research, whether it will be weather forecasting, aviation meteorology, agricultural meteorology, hydrometeorology, nuclear meteorology or maritime meteorology.[136] If we assume that he works on weather forecasting, he will initiate his observations and analysis with a determined theory that will rule and structure the whole modeling process. In this manner, he will have a leading pattern and technique to continue his observations and analysis by detecting the factors and agents that are determinant on the alterations in weather conditions, and by questioning the interconnections of these factors and agents with each other. From the numerous variables that exist in the atmosphere such as temperature, air pressure, water vapor, etc., the scientist needs to define the relevant data that is mandatory for the model to build a complete and consistent system. Through experimenting the model with generate-test cycles[137], he will configure insufficiencies or fallacies of the existing model. In other words, he will learn from the model the points where he needs to make modifications or advancements for a more precise system. Therefore, the scientist establishes another learning process, which is nested in the global research cycle and catalyzed by the communication of theoretical construction and factual novelty. In the total outlook, the mode of thinking, which the scientist has adopted, leads the process of modeling, and vice versa

[135] Herbert Simon. *The Sciences of The Artificial*. Massachusetts: MIT Press, 1972. p. 2.

[136] C. Donald Ahrens. *Meteorology Today: An Introduction to Weather, Climate, and the Environment.* Belmont, CA: Brooks/Cole, CengageLearning, 2009.

[137] Generate-test cycles and the modeling process will be explained in detail further more in the following chapters 5.

the model is the manifestation of the idea.

Natural sciences intend to explain the reality and actual phenomena of the universe, while on the other hand the fields of engineering and architecture intend to configure the possibilities and contingencies of the man-made. Herbert Simon clarifies this departure by stating: "The engineer is concerned with how things ought to be – out to be, that is, in order to attain goals, and to function."[138] These goals are numerous and interwoven in a complex structure including various aspects of a building such as environmental compliance, economy of material and energy, sociological and psychological impacts, stability and statics, manufacturing and assemblage, etc. Therefore, architecture and natural sciences raise distinct products; yet both construct similar complex systems that generate an outcome.

Moreover, Simon mentions the dichotomy between normative and descriptive manners of the disciplines concerned with the artificial and natural.[139] Engineering and architecture are concerned with design and artificiality; thus they have a normative manner of qualifying their objects. On the contrary, natural sciences are concerned with the existing, and they approach the object of research in a descriptive manner. The distinct approaches of engineering and natural sciences to lotus plant can illustrate the difference between the normative and descriptive approach. Biology has discovered and defined the self-cleaning property of lotus leaves named as the 'Lotus Effect', while engineering has interpreted the determinants of such effect to mimic this behavior in building paints. Biological investigations on the lotus effect have connected this character to the extremely rough surface of the leaves. In this manner, the leaves hardly collect dust and dirt; moreover they are easily washed with rain. Inspired from this, the engineers of the paint industry have focused on this quality of Lotus and developed a self-cleaning paint called Lotusan. They translated the super-hydrophobic (high water repellency) function of the natural to the artificial, by redefining its generative factors.[140] In short, biology examined the existing mechanism of Lotus leaves in a descriptive manner, while engineering redefined the existing with new rules and materials in order to achieve the intended goal.

On the other hand, architectural interpretations of lotus have stayed at the level of resembling lotus plant, without any rule-based inferences.[141] Thus, architecture needs to draw its own

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[138] Herbert Simon. *The Sciences of The Artificial*. (1972) p. 5.

[139] *Ibid.*

[140] http://www.paintpro.net/Articles/PP705/PP705_ProductProfiles.cfm Last resumed at 09.09.2011.

[141] Interpreting the architectural products that are derived from lotus plant, such as: The Lotus Temple at New Delhi, The Parnasala at Kerala, and The ArtSceince Museum in Singapore.

computational models for transcoding specific data/ property/ function from nature to man-made. In this thesis, both descriptive interpretations and normative implications of the cactus have been discussed. Comparable to Lotus Effect and its implications for building paints, the water and humidity collecting, and self-conditioning property of cactus plants have been evaluated as promising for architectural form generation. Similar to the detection that marks out the rough surface of lotus plants leading the super-hydrophobic function, the spiral arrangement of areoles has been analyzed as the crucial parameter of water collecting and self-cooling behavior in cacti. This arrangement creates spiral water channels, which act as air-vent pipes at the same time. Thus, once the determinants, parameters, and variables of this mechanism are structured in a complete computational model, the same function and behavior can be regenerated for establishing a similar passive environmental conditioning in architectural products.

Both in nature and architecture, there are a vast number of embedded goals, which are derived by the necessity of finding a balance between the inner system and outer environment.[142] In natural organizations, the inner system may refer to the genetic system of growth or the mechanism of process, where as the outer environment includes the variables and parameters that are determinant components of the system. Similarly, artificial organizations try to form a consensus between the inner system and the outer environment. The outer environment may refer to user or designer input, values of variables, and other agents that are active in the arrangement of the system. Within this scope, Simon regards artificial entities as interfaces:

> "An artifact can be thought of as a meeting point – an "interface" in today's terms – between an "inner" environment, the substance and organization of the artifact itself, and an "outer" environment, the surroundings in which it operates."[143]

Computer as an interface differ from others with its capacity of being accessible and flexible. They are accessible because they work in a specific structure and with a specific language; thus it is possible to communicate and collaborate with a computer in order to reach nested interfaces. They are ductile because the configuration of the inner system allows making changes and modifications within specific limits and regulations for systematic progresses or modifications. To illustrate, a computer may be compared with a pencil in terms of their capacity of meeting a goal. In the case of the pencil, how well it is going to write depends on the quality of the pencil, of which the variable of the inner system may be counted as the ink

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[142] Herbert Simon. *The Sciences of The Artificial*.(1972) p. 9.

[143] *Ibid*. p. 7.

and the pen point, and the external inputs as the paper, metal, or glass writing surface medium. If the pen doesn't work well on metal surfaces, the user either changes the pen or the surface that is introduced. On the contrary, in computers when there is a similar situation of inadequacy of outcome, the user may interfere with the computer's inner structure and establish modifications in order to develop the interface as a better fit for the goal it targets. Therefore computers are easily accessible, open-ended and dynamic rather than static; within the simplicity of their underlying principles, they embrace the potential to represent/ model/ run various systems, from the simple ones to very complex processes.

It shall be scrutinized that computer as an interface holds other artificial interfaces nested within itself; it has an agile structure. The user may interact with the interior sub-interfaces only through the meta-interface of computer; thus he/she is forced to think and model in terms of computation. In this way, computer begins to act as an extension of the mind. Computers happen to be the meta-interfaces to model sub-interface systems, while computation proposes the mode of thinking, the set of structures and methods appealing to it. Herbert Simon declares the stringency and accuracy in computational systems:

> "A computer is an organization of elementary functional components in which, to a high approximation, only the function performed by those components is relevant to the behavior of the whole system."[144]

Computers present restrictions, limits, rules and boundaries. Clive Dym argues that mathematical modeling is a principled activity, which can be compared with computational modeling; and it is formed by the meta-principles of mathematics and the mathematical literacy.[145] Furthermore, computational meta-principles are the active determinants of models, structures, processes and representations of the sub-interfaces nested in computers. In this thesis, the interface for modeling cacti has been decided as Monkey Script Editor, which is a plug-in of Rhinoceros 3D Modeling program. Monkey operates with the scripting language named Visual Basics and in accordance with the Rhinoceros' geometry construction algorithms. However, even though Monkey is a plug-in and sub-interface located in and dependant on Rhinoceros, it is through Monkey that a complete algorithmic mechanism to generate cacti can be implanted in Rhinoceros. It is difficult to establish a sub-meta hierarchy between Rhinoceros and Money. Yet it can be inferred that as the interfaces get more nested and layered within each other, the language shifts from natural language and simple commands towards symbolic language and computational meta-principles. In the cactus studies mentioned in this thesis, modeling cacti by scripting has served to comprehend

[144] *Ibid*. p. 18.

[145] Clive L. Dym. *Principles of Mathematical Modeling*. Amsterdam ; Boston : Elsevier Academic Press, 2004. p. 6.

and re-construct the generative system within an algorithmic structure and through essential computational principles. As a meta-interface, computers force the user, who aims to interact with a nested-interface computer program, communicate and construct his/her arguments in computational language and operations, with computational structures of information processing. Hence, in this way computation becomes the major mode of thinking and 'transcoding' specific data from one domain into another. In this respect, transcoding transfers the process-based information through sequentially decoding and encoding through computational rules, operations, and principles. The ever-ending loop of analysis and synthesis establishes a simultaneous practice of encoding and decoding throughout the process of constructing transcoding models.

3.3.2. Computation as ***Transcoding***

In the search of possible architectural solutions as an extension of natural organizations, architecture needs to construct its own computational models of natural phenomena in order to comprehend and reinterpret processes of natural form generation. Rewriting the systems of natural and man-made organizations with computational principles brings forth a new vision towards life, as well as presenting a new method of generating them in the discipline of architecture. Michael Weinstock affirms computational association of the man-made and natural organizations emphasizing its potential impacts on expectations from built environment:

> "Architecture is on the cusp of systematic change, driven by the Dynamics of climate and economy, of new Technologies and new means of production. There is growing interest in the Dynamics of fluidity, in Networks and in the new topologies of surfaces and soft boundaries. This is part of a general cultural response to the contemporary reconfiguration of the concept of 'nature' within the discourse of architecture; *a change from metaphor to model*, from 'nature' as a source of formal inspiration to 'nature' as a mine of interrelated dynamic processes that are available for analysis and digital simulation. [Author's italics]"[146]

The "systematic change" in how we interpret our environment and how we apply that knowledge into man-made organizations fundamentally derives from computational thinking and the mindshift it leads to. Interpreting theory as a mediatory device for understanding two or more different types of entities, Frederic Jameson puts forth the concept of "transcoding": "the invention of a set of terms, the strategic choice of a particular code or language, such that the same terminology can be used to analyze and articulate two distinct types of objects

[146] Michael Weinstock. "Metabolism and Morphology." *Versatility and Vicissitude: Architectural Design*. Vol 78 No 2. p. 26.

or 'texts,' or two different levels of structural reality."[147] As a form of transcoding, computation is an interface to interpret and express natural and artificial reality as a total system instead of explaining only some fractions or properties. As computation provides a uniform framework in which to discuss different processes, it is possible to think of any process that follows definite rules as being a computation – regardless of the kinds of elements it involves.[148] Moreover, with the idea of computational transcoding, the universal processes occurring in each entity can be comprehended with the same constructive demonstration, enabling conversations of knowledge between distinct disciplines.

3.3.3. Computational Models for *Transcoding* Architecture and Nature

Computing theory and algorithmic thinking led enthusiastic challenges to explain natural and artificial phenomena. In other words, computation as a *transcoding* interface became both the major guide and medium in the search for describing the universe and its systems in their algorithmic totality. Traditional mathematics and static systems stay numeric and deficient to uncover and clarify the complexity of nature in a complete and integrated system. The distinct 'mindset' of computation, computational concepts and theories led the exploration to explicate natural processes in a different model, which establishes a dynamic generative mechanism that basis on the specification of relations and dependencies. For instance, parabolic spirals, which can be observed in numerous natural organizations, have been explained with the sequence of Fibonacci numbers or Vogel's mathematical formula(Fermat's Spiral).[149] Computation provides another model and understanding the curves in nature. Such that, its computational resolution doesn't base on numbers or spirals defined by Fibonacci series. But these defined curves can be interpreted as solely one of the possible outcomes of a generative system.

In the search for establishing complex behavior in artificial systems, computational processes that behave emergent shall be counted as predecessor attempts: cellular automata, and L-systems, which try to model the information flow of natural organizations. In cellular automata, initial rules are operated in several generations with self-organization and

[147] Quoted in K. Michael Hays. "Introduction." In Michael Hays ed., *Architecture Theory Since 1968*, an anthology. Cambridge MA: The MIT Press,1998.
Original in Frederic Jameson. *The Political Unconcious*. Ithaca: Cornell University Press. 1981. p. 40.

[148] Stephen Wolfram. *The New Kind of Science.* p. 716.

[149] Przemyslaw Prusinkiewicz, Aristid Lindenmayer. The Algorithmic Beauty of Plants. Springer-Verlag. 1990. pp. 101–107.
It can be reached online from: http://algorithmicbotany.org/papers/#webdocs. (Last Resumed at 03.12.2011)

repetition where each step is defined by the previous stage and determinant on the next. Thus, the local cellular interactions define the global outcome. Even though the first inputs such as rules, relations, and parameters are simple, the system may emerge into a complex ending. As a branch of research on cellular automaton, L-systems proposed a process for modeling the growth of plants. [150] Moreover, the concept of morphogenesis brought forth new models to enlighten such phenomena, while at the same time this approach presented new insights for architecture to use digital media as a generative mechanism for process of design. On the generative aspect of morphogenetic approaches in architecture, Branko Kolarevic states:

> "The digital generative processes are opening up new territories for conceptual, formal and tectonic exploration, articulating an architectural morphology focused on the emergent and adaptive properties of form. The emphasis shifts from the "making of form" to the "*finding of form*," which various digitally-based generative techniques seem to bring about intentionally. In the realm of form, the stable is replaced by the *variable*, singularity by *multiplicity*."[151] [Author's italics.]

The divergence of form-finding derives from the comprehension of form as an outcome of a dynamic generative mechanism rather than an absolute end-product. In form-finding, the coordination between the generative mechanism's determinants is specified within their relations, dependencies and functions. In this manner, the system that can give rise to various and diverse outcomes is structured. From this perspective, computation proposes a distinct mind-set as well as the media and literacy to construct dynamic parametric models of form in the use of architectural inquiries. Kolarevic goes on defining taxonomy of computational techniques for architecture including new territories as key shape animation, genetic algorithms, topological architecture, and blobs. Yet, it must be noted that, these approaches towards computational architecture shall not be comprehended as the only alternatives for computational models. There can be numerous generative models that architecture can base its inquiries upon. For that reason, architecture needs to define and construct its own models, reference systems, and generative processes. The generative system, its parameters, variables, inputs and its interrelated information flow structure needs to be reorganized depending on the scope, aim, and function of the architectural project. Therefore, the

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[150] Ibid.

Ingeborg M. Rocker. "When Code Matters." p. 21.

[151] Branko Kolarevic. "Digital Morphogenesis." *Architecture in the Digital Age: Design and Manufacturing*. Edited by Branko Kolarevic. New York: Spon Press, 2003. p. 13.

research in computational architecture shall not be limited with the existing taxonomy of computational models.

There is an organized complexity in nature: many variables and interactions with an underlying definable structure. Emergence theory is introduced to explain natural phenomena with properties such as self-organization, pattern recognition, feedback mechanism and indirect control by adaptive learning. Emergence, in its common meaning, describes an entity, which is more than the sum of its parts: "a complete system which cannot be reduced to their sum or their difference."[152] Emergent behavior appears at different scales of natural and man-made organizations, from interactive increment of cells to ant colonies, from software systems to cities' growth. [153]

Michael Weinstock argues that there is a lot for architecture to learn from emergent systems, from their mathematical basis of processes where high-level entities are constructed from the low-level interactions:

> "The task of architecture is to delineate a working concept of emergence and to outline the *mathematics* and *processes* that can make it useful to us as designers. This means we must search for the principles and dynamics of organization and interaction, for mathematical laws that natural systems obey and that can be utilized by artificially constructed systems. We should start by asking: What is it that emerges, what does it emerge from, and how is emergence produced?" [154] [Author's italics.]

To illustrate Weinstock's argument, cactus has been analyzed in this thesis through considering these three questions about emergence as the leading information to build a computational model. The emerged behavior is observed as the water collecting and self-cooling property of cacti. This behavior emerges from the spiral configuration of the areoles and areole hills, which compose water channels that act as air-vent pipes concurrently. Consequently, once the production process of this spiral configuration is clarified in a parametric model, architectural implications of such process can be explored within a similitude of behavior with the cactus.

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152 The Emergence and Design Group. "Emergence in Architecture." *Emergence: Morphogenetic Design Strategies: Architectural Design.* Vol 74, No 3, 2004.

153 Further reading about emergence of various systems can be found in the book: Steven Johnson. *Emergence: The connected lives of Ants, Brains, Cities and Software.* New York: Scribner. 2004.

154 Michael Weinstock. "Morphogenesis and the Mathematics of Emergence." *Emergence: Morphogenetic Design Strategies: Architectural Design*. Vol 74, No 3, 2004. p. 11.

Transcoding through computation flourishes an interdisciplinary environment in architecture with the contributions of incoming information from biology, genetics, computer science, mathematics. It shall be reminded once more that computation as 'transcoding' first decodes the information of various disciplines under the same syntax. Secondly, this decoded data is rebuilt with computational structures for conducting a more specialized assignment in the relevant work environment. In this way, architecture turns into a collaborative study where each kind of data finds its own place accurately and interacts accordingly with the over-all information structure. In other words, the information flow is organized in such a way that any local input of information has its consequences in the global outcome. The over-all design evolves each time the parameters are revaluated, leading to performance-based conclusions for architectural products. For example in the cactus model explained in the following chapters, there is web-like interconnected structure of the generative system. Thus, while the initial input of a polygon alters from a pentagon towards an octagon, the overall outcome form and its hydro-dynamic performance is renewed. If the process of constructing the cactus model included an expert from hydro-dynamics study area as well, the model would accept more inter-disciplinary inputs. For instance, according to the multi-dimensionality of the information flow structure, the global form could generate within the participation of hydro-dynamic performance value.

With the rise of computational thinking, nature began to be observed in a diverse way that was enlightened with the collaboration of many disciplines; the edges between different disciplines have turned into vague.[155] The new way of scientific thinking, computation, has gained strength with discoveries in biology, physics and the contribution of mathematics. Relatively, the branch of philosophy of science and nature has been reformed.[156] Now natural processes can be integrated into architecture, with the changes about how we analyze and interpret natural organizations. Correspondingly, the information extracted from cactus through computation differs from previous attempts. Through computation, cactus is analyzed for its integrated, dynamic and performance-based generative system, and the information flow structure establishing such system. Consequently, learning/revisiting nature through computation opens up new visions in generating architecture. Biological concepts are beyond just being example or inspiration to obtain soft forms for architecture. They provide us observable real cases to learn about the process of systems, natural and artificial.

[155] The Emergence and Design Group. "Emergence in Architecture." p. 6.

[156] Whitehead's objections towards the previous theory of nature are stated more in detail in his book: Alfred North Whitehead. *The Concept of Nature*. Cambridge the University Press, 1964. p. 39.

3.4. Emerging Trans-Disciplinary Environment in Architecture

The disciplines have lost their strict boundaries, while with interactive feedbacks they are embracing a common idea of algorithmic procedure to understand the universe, its systems and its processes. Kostas Terzidis explains algorithm by saying that "an algorithm is not only a computer implementation, a series of lines of code in a program, or a language, it is also a theoretical construct with deep philosophical, social, design, and artistic repercussions."[157] Accordingly, it can be concluded that by the introduction of algorithms and systems working with representation, *how* we think began to be discussed more than *what* we think.

The question of how mind works became a favorite issue to discuss in the early years of 20th century with the arising of logical positivism, implying the way of thinking and expressing an idea can be decreased to initial basic elements and rules. The architectural approach of the era has been erected upon the metaphors of *building, brick* and *construction,* and the idea of constructing a complex system from simple initials.[158] Now, it is possible to rewrite these metaphors as *pattern/model, operation/code, and algorithm*, similar to Karl Chu's interpretation of the well-known quote of modernism by Mies van der Rohe 'the art of putting two bricks together' as 'the art of putting two bits together'.[159] Hence, the idea of a system emerging from local interactions with simple initials and rules has been governing the discipline of architecture for a prolonged period of time. However, as the modeling tools and medium have developed in a great extent, the comprehension and application of the computing theory in architecture has evolved towards the contemporary architectural inquiry. Algorithmic thinking has rejuvenated the explorations for unprecedented architectural products and solutions, since it highlights local interactions between parts, and their global relational network structure within the totality of design.

On the other hand in the discipline of biology as well, the developments and discoveries in genetics have been also supporting and embracing the idea of codes and algorithm that lay in the base of all living organisms that would rule their growth and pattern development. In the case of biology, the code of an algorithm is named as the genetic code, which ascertains

[157] Kostas Terzidis. *Algorithmic Architecture*. p. xiii.

[158] Peter Gallison. "Aufbau/Bauhaus: Logical Positivism and Architectural Modernism." In *Critical Inquiry*, n. 16, 1990.

Abbott J. Miller. "Elementary School." *The ABC's of [Yellow Triangle, Red Square, Blue Circle]: The Bauhaus and Design Theory*. Edited by Ellen Lupton and Abbot J. Miller. New York: The Cooper Union for the Advancement of Science and Art, 1993.

[159] Conversations with Karl Chu, in the lectures of *Genetic Architecture II*, ESARQ-UIC, Barcelona, March 2008.

form and pattern. The recent ideas on biological growth and form generation, such as interactive feedback mechanisms, self-organizations of parts, metabolism equilibriums are constituted with the support of computational thinking as well. Emergence theory puts forth the idea that specific interactions between local elements may generate a highly complex and unpredictable outcome, which is greater than the sum of its parts.[160] As an example for emergence, ant colonies may be assessed to imply more than the sum of numerous individual ants; ant colonies confirm the collective intelligence rising from the micro behavior of individual ants.[161] It can be observed that ants follow a single path while they are leading towards a food source and carrying the collected food back to their home. Although a number of ants are travelling on the same route through this process, they neither collide on each other, nor do they go astray.

Moreover, there is no hierarchical job organization in an ant colony; no ant is commanding the crowd to lead towards a specific direction. However, it is observable that there is a ruling system other than hierarchical that establishes such an order. Edward O. Wilson has proved that this order in collective ant movement derives from a local interaction based on 'pheromone' communication that takes place between individual ants by pattern recognition and feedback mechanisms.[162] Each ant leaves pheromone behind when they travel through a path. Likewise, each ant has the genetic behavior of following the pheromone trail. In this way, as more ants pass through a route, the accumulation of pheromone becomes determinant on the decision of the most preferred route between the food source and ant nest. To sum up, the emergence of the global collective intelligence depends on the local pheromone pattern recognitions and feedbacks of individual ants. A similar mechanism occurs in the internet – 'global brain': the search motors are showing the most preferred website results related to a specified keyword.[163] To sum up, it can be concluded that there exists an algorithmic structure in a colony of ants that can be uncovered. The complexity of such phenomenon can be explained through configuring the simple local interactions and operations of a global algorithmic system.

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[160] "The whole is greater than the sum of its parts." was first told by Aristotle. Later, liberalizing from its original speaker, it became the major expression to explain the comcept of emergence.

[161] Steven Johnson. *Emergence: The connected lives of Ants, Brains, Cities and Software.* New York: Scribner. 2004. p. 30.

[162] Ibid. p. 52.

[163] By chasing the footprints of Internet users, the relations between websites are drawn. More explanations about the construction of connections in the Global Web can be found from:
Ibid. pp. 113-126.

In various disciplines of science and engineering, the world has discovered the potential of symbols[164] and algorithms, how they exist in all the animate and inanimate organizations around us, and how they are capable of controlling the overall organization growing from the very beginning with simple initial rules. In this way, the computational paradigm traversed many disciplines; philosophical thoughts, mathematical researches, biological discoveries and the invention of the computing machine are weaving the disciplines of basic sciences with each other. Through this process, the disciplines were exchanging, sharing, bracing and feeding each other's ideas with their multi-directional information transfers and feedback loops, praising an interdisciplinary and even trans-disciplinary environment.[165] Decentralized networks can be compared with the disciplinary settlement in contemporary universities: several departments collected under faculties, which are connected to a center. Yet, there occur fallacies in the communication between distinct faculties. It can be questioned if Paul Baran's distributed communication network configuration can alter this decentralized and departmentalized structure of scientific knowledge towards a trans-disciplinary environment.(Figure 3.8)

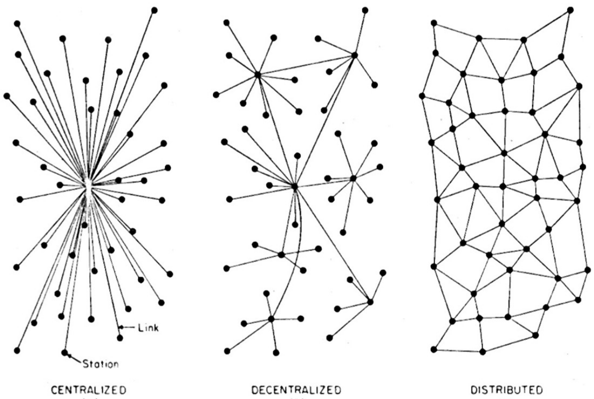

Figure 3.8 Paul Baran's idea of distributed networks for communication.

Graphics from: http://www.rand.org/pubs/research_memoranda/RM3420/RM3420-chapter1.html Last resumed at 11.09.2011.

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[164] Symbols are referred as the vocabulary of a constructive system and syntax concluding to a symbolic system. As a foundamental example, the binary vocabulary of computers can be counted as basic symbolic language.

[165] Prof. Mark Burry from RMIT puts his own explanation of the term 'trans-disciplinary' as: "'Transdisciplinary', put simply, means teams of designers who assert their professional expertise within a diverse group of creative thinkers, but in working closely with other design disciplines, enrich their own with new understandings that come from working towards a shared solution or concept."
http://rmit.edu.au/browse/Our%20Organisation/Research/Research%20Institutes/Design%20Research%20Institute/ last resumed at 03.01.2010.

Architecture is a trans-disciplinary study; architectural knowledge is comprised of information from various disciplines, such as mathematics as an abstract construction, engineering as an application of specialized data in reality, and social sciences as a research in human-made world. The overall non-linear structure of information flow, which is determining the relationships and dependencies between several nodes of expertise in architectural practice, is the underground mission of the individual architect. The role of an architect includes introducing a complete system, which will enable harvesting all the numerous data under a logical construction such that it will be possible to generate architectural products that are results of an associated information network. In this framework, it shall be noted that the Cacti transcoding shall be further studied and completed in a more transdisciplinary environment that is beyond the scope of this thesis.

Although the trans-disciplinarity argument in this thesis does not directly derive from Novak's interpretations of computer aided architecture and digitalization, it should be noted here that Marcos Novak also mentions a transdisciplinary work environment in his proposal of the term "transarchitectures" as the new approach for practicing digital architecture. Novak identifies transarchitectures as practicing transformation, transmutation, transgression of reality into information through digital tectonics, mediums and algorithmic descriptions. In his statements, transdisciplinarity is mentioned as the recently developed multi-layered work domain, which can be counted as having a higher degree of collaboration within merged and collapsed disciplinary boundaries than the terms of 'multi-disciplinary' and 'inter-disciplinary' studies. Novak asserts that a multitude of transdisciplines have been formed as a result of the changes in the comprehension of reality through algorithmic structures (morphogenesis), modeling and building numerically by new tectonics(rapid prototyping).[166]

Computation presents both a theory and a medium for architecture. Computational transcoding acts as a theory to understand the systems of our environment, natural and man-made, biological and architectural, as well as a medium in the transfer and application of the extracted knowledge. Computation, as transcoding and as an interface for trans-disciplinary knowledge constitution, instructs analyzing, understanding and reinterpreting the in-formal structure of natural organizations (such as system, information flow, and process through time) for artificial form generation. Therefore, through the cacti case study, the inner logic and in-formal properties of cactus shall be focused on rather than its formal properties.

[166] Marcos Novak. "Transarchitectures and Hypersurfaces: Operations on Transmodernity." Chapter in *Architecture and Science: Architectural Design*. Great Britain: Wiley Academy, 2001. pp. 153-157.

However, it shall not be ignored that form is a major determinant of performative behavior and response to environmental conditions.

Since computational models have been capable of representing and depicting more complex and comprehensive information flow structures, it is possible to model a multi-dimensional information exchange network in architecture. Throughout the transcoding process of nature to architecture, the information structure of the computational model evolves from a simple schema towards a more interdependent, associated, relational and comprehensive generative system. Thus, the model necessities data from several disciplines other than architecture; the model, then, should indicate the plugs of determinants and parameters, which belong to the expertise of other disciplines. In this manner, the model can be developed with the participation of several disciplines, while the general layout of the system is still under the control of the architect. From this perspective, the architect is responsible for determining the knowledge to transcode and also for structuring and modeling the generative process deriving this knowledge in totality.

Since in natural systems, knowledge of a type of behavior is interconnected with several properties, the transcoding computational model needs to embrace and structure all the determinant aspects on the intended transcode behavior. Therefore, the architect needs to construct a complete system, precisely complex or highly abstracted. And in order to establish a complete system he/she needs to draw a comprehensive parametric map including determinant data. For instance, in a study of transcoding the aerodynamic behavior of sponges to panel walls,[167] the architect needs to determine which of the following aspects - sponge geometry, solid-void density, magnitude of voids, material, sunlight exposure - are determinant on the aero-dynamic property and how they are determinant on it. In this manner, the transcoding will be established through a parametric model of the sponge, where a local alteration in an agent is determinant on the global outcome. Relatively, all the determinant aspects of a specific behavior shall be considered as the constituters of the generative system from the initial analysis phase of transcoding and modeling process. Similarly in the cactus studies, the water-collecting, self-shadowing, and self-air conditioning behaviors will be analyzed in the aim of specifying the generative determinants, parameters, and their relations. In the following section, the cacti will be de-coded regarding the formal properties and aspects that emerges such performative behavior.

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[167] This example is given in reference to the study of Garin from AA that has been mentioned in Chapter 2, in the section '2.2.2.2. Porous Models.' The wall panels have been inspired from sponge and diatome structures.

Consequently, it can be questioned if the knowledge range of architecture needs to expand, or if once more architecture searches the Renaissance man – a polymath, who has knowledge in many study fields. In a transcoding process, the architect constructs interrelations, dependencies, builds algorithmic systems, determines parameters and variables that will lead to the similitude of behavior. Therefore, the architect needs to gain insight (although not an expertise) about the scientific knowledge focused at various disciplines in addition to having the reasoning capability for structuring their association. In this perspective, as the aim of the practice evolves to transcoding, architecture becomes a trans-disciplinary study. And vice versa, the trans-disciplinary environment, which has been possible with the advent of information technologies, brings forward a demand for transcoding that will transfer the process-based behavioral intelligence of nature to architecture.

CHAPTER 4

TRANSCODING I: DE-CODING THE NATURAL GENERATIVE PROCESS

THE DE*SCRIPT*ION OF CACTI

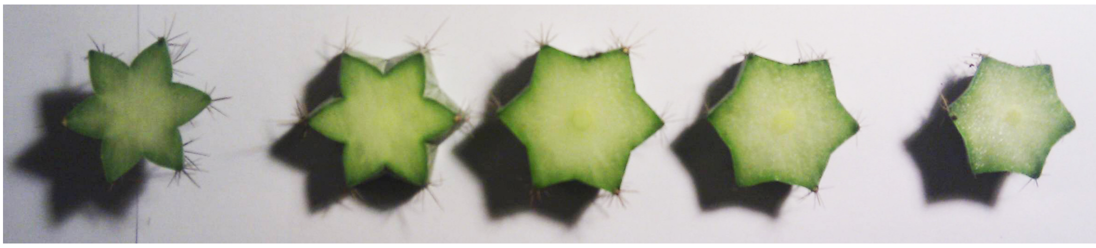

Figure 4.1 Dissections of Polaskia Chichipe type of cacti. [Photos by the author]

> "Thus, the architects wishing to use this new tool*[genetic algorithms]* must not only become hackers(so that they can create the code needed to bring extensive and intensive aspects together) but also be able "to hack" biology, thermodynamics, mathematics, and other areas of science to tap into necessary resources."[168]

As it is explained in the previous chapters, throughout history the association between nature and architecture has been ascertained by assigned 'mediatory link's that would decode the order in nature and encode this information for architecture. Through this exploration seeking for order, proportion, mathematics, physical models have served for linking architecture and nature by their constructs and tools. In this thesis, computation is considered as the 'mediatory link', which instructs and shapes our mode of thinking, understanding, interpreting nature. Additionally, computation presents us mediums and tools for modeling knowledge in a complete system.

[168] Manuel DeLanda. "Delueze and the Use of the Genetic Algorithm in Architecture." in *Phylogenesis: foa's ark*. Edited by Foreign Office Architects. Barcelona: Actar, 2004. p.529.

Knowledge constitution is a conclusion of a mutual relationship between factual novelty and theoretical construction. The extracted information eventuates from both the existing phenomena and the human way of structuring it. In this chapter, computational thinking and computational mediums have been the locomotives in constructing the generative system as a model.

Transcoding of process-based knowledge from one domain to another depends on the practices of decoding and encoding. In this thesis, computation is regarded as the linking mechanism – the mediatory device between the natural and architectural domain. The theoretical framework and medium that computation presents will structure, limit and liberate the transcoding model. In other words, the transcoded knowledge is constituted and limited within the structural constraints, principles and operations that the model may express. At the same time, the computational model is shaped depending on the scope of transcoding. Therefore, there is an intertwined and interdependent relation between the process of transcoding and modeling i.e. between theory, medium and goal.

Transcoding of natural processes as a part of architectural form finding inquiry initiates from the observation and analysis phase. The decoding of natural phenomena illuminates and orientates the whole process and structure of the transcoding model. Since transcoding involves simultaneous decoding and encoding, the architect needs to participate in the whole process from the initial observations and analysis, to the construction of computational models. Thus, only through participating in the transcoding process form the very beginnings, the architect may have control on the architectural outcome. In this manner, he/she will dominate the generative process and will be able to make interferences at any stage of the model in order to lead the outcome towards a satisfycing solution.

From this perspective, the architect's responsibility is not limited with the architectural design process or product. On the contrary, his/her main interest is the knowledge transcoding between nature and architecture. Thus, which knowledge from nature is going to be transferred, in which mode of information structure and medium it shall be modeled, and how it shall be interpreted for well-established architectural solutions are the main research subjects of such an architectural inquiry. Moreover, the architect as the modeler orientates the model according to the particular knowledge that he/she intents to inherit.

In this thesis, the process of modeling i.e. constructing 'transcode's between nature and architecture will be examined with a case study on cactus plants. It shall be noted that the main interest of this thesis is neither the object of study specifically as the cactus nor the architectural product the study envisages. Ian Stewart, whose research is focused on the underlying mathematical principles existing in nature, emphasizes that scientific research shall be ‘curiosity-driven’ instead of object-oriented. Stewart claims that ‘curiosity-driven’ research possesses the character of unpredictability and thus a higher potential for discovery.[169] Correspondingly, computation shall be regarded as a mode of inquiry for obtaining knowledge from nature and applying it to architecture; not with an intention of establishing an end-product but with an intention of learning, and learning about processes. Similarly in the case study of this thesis, cactus plants are examined in order to obtain a process-based knowledge within a curiosity driven inquiry.

Hence, the main interest of the case study is to examine the processes of modeling, learning, and transcoding. In this respect, the decision of cactus plant shall be regarded as one of the many alternative natural organizations that could be studied. However, it shall be added that the behavioral, functional and geometrical properties of cactus are assessed as valuable and potential for such an inquiry aiming to obtain architectural products. One of the main reasons of such an assessment is the broad variety of geometrical forms that can be encountered in cactus species. Moreover, cactus plants are skillful in collecting water, shadowing and air-conditioning their body, which can be appraised as the desired functions for contemporary buildings. In the inquiry for modeling, these two properties –geometry and function- will be considered as overlapping and integrated driving forces of form generation, both in architecture and nature.

Following Simon’s description for interfaces, natural organizations can be regarded as interfaces between their genetic coding and their environment. The genetic code includes determinant rules of growth, shape, function, color - in sum everything belonging to their morphogenesis. Yet, morphogenesis defined by the genetic code stays still dependent on and modified by the environmental conditions. For instance, plants cannot change their locations much like buildings; they have progresses in order to adapt, react, and interact with the environmental conditions in order to survive by establishing mutual relationships with their surroundings and inanimate nature. Thus, they have developed capabilities of producing energy for themselves (photosynthesis), solar tracking and moving towards the light (phototropism), orienting their roots towards a water source (hydrotropism), being stable and flexible under the wind force. Moreover, their growth develops dependent on the physical conditions of the environment; and yet they continue to embrace common formal properties amongst their variety. Thus, one plant specie presents numerous varieties of outcomes

[169] Ian Steward. *Nature's Numbers: The Unreal Reality Of Mathematics*. Basic Books, 1995. p 28.

emerging from the same generative system as a result of the alterations in the environmental inputs and parameters.

Swarm behavior has been subject to various researches that examine the hidden order underlying the growth of a swarm under different conditions.[170] These researches have been conducted within the scope of emergence phenomena, where simple initials, agents, and rules lead to complex systems at the edge of chaos. However, there are simple common traits of natural organizations, animate or inanimate: self-organization and neighbor interaction, pattern recognition and goal direction, negative and positive feedback.[171] Thus, animate and inanimate natural organizations, ranging from ant colonies to urban cities, are dynamic complex systems. They embrace association and repetition of simple rules within a margin of modification; consequently, the aggregation of these simple rules ascertains the global outcome.

Genotype and phenotype are terms describing such dual behavior of form generation in natural systems. Genotype refers to the genetic rules of a natural form generation, whereas phenotype refers to the external factors effecting and orientating growth.[172] In this context, natural organizations intend to build and maintain equilibriums between their genotype and phenotype properties. Similarly in architectural buildings, there is a mandatory balance between the function and form of the building and environmental conditions. Buildings need to fulfill air circulation necessities, light requirements, heat and shade provisions for establishing equilibriums of the inner metabolism.[173] Consequently, there is a similarity in natural and architectural form production; both need to serve the functional goal of establishing equilibriums between the inner and outer system in order to operate successfully. Hence, such equilibrium emerges from a dynamic complex system, about which natural systems may instruct/ illustrate/ illuminate architecture.

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[170] Within the scope of emergence, artificial intelligence and computer science; swarm behavior, flocking, and ant colonies have been examined concurrently. Some examples can be found in: Floreano, Dario; Mattiussi, Claudio. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. Cambridge, Mass: MIT Press, 2008. pp. 522-547.

Johnson, Steven. *Emergence: The connected lives of Ants, Brains, Cities and Software.* New York: Scribner. 2004.

[171] *Ibid.*

[172] Stanislav Roudavski. "Towards Morphogenesis in Architecture*." International Journal of Architectural Computing*. Vol 07, Issue 03. pp. 345-374.

[173] Michael Weinstock. "Metabolism And Morphology." *Versatility and Vicissitude: Architectural Design*. Vol 78, No 2, 2008. pp. 26-33.

4.1. A Case From Nature: Cactus

In this thesis, the case of cactus plants will be studied with an intention of constructing a computational model of their generative mechanism of form and performance. The water collecting, self-air conditioning, and self-shadowing capabilities of the cactus are collaboratively operating with the overall form of its body and the spiral configuration of areoles. Thus, these performative behaviors that is common to most of the cacti species will be considered as crucial features to transcode from nature into architecture. The transcoding model of the cactus will be constructed in the interface of Rhinoceros 3D Modelling program and it will be developed, constructed, and shaped by Monkey Script Editor, which is a scripting plug-in working with Visual Basics code language in Rhinoceros. Through this process the cactus plants are going to be [re]analyzed, [re]comprehended, [re]constructed within the principles, limitations, and potentials of a scripting practice.

Figure 4.2 Variety in the Cactus family is observable in this small section of particular types.

Photos collected from: http://www.cactus-art.biz/gallery/Photo_gallery_abc_cactus.htm Last resumed at 11.09.2011.

The Cactus family is a highly populated group, where exists an extensive variety of phyllotaxis configurations, growth regulations, color pigments, areole patterns, and flowering types.(Figure 4.2) Yet, they conjure up connotations of a shared order, which is generated through common rules and principles. In the next chapter, the common order of the cactus family will be examined in a computational set-up, that resolves the generative agents, parameters, variables of the overall form and the information, dependency structure governing them. In this respect, the members of the cactus family will be regarded as several outcomes of such a computational model.

Through modeling, the key properties that are to be transcoded from cactus will be considered as the structure of geometric properties deriving the global form and the water collection/ storage capacity within that form. Michael Weinstock points out allometry as a key for understanding natural organisms and states that the metabolic and morphologic properties of a mass is dependent on the volume of the organism.[174] Thus, if the cactus is systematized in an integrated model that associates geometry, volume/form, and behavior, the generative process is likely to establish similitude of behavior in addition to the variety of probable generations.

In this thesis, the phyllotaxis of areoles will be acknowledged as crucial, since their configuration and order is considered as the generator the global form in addition to the waterways that orientate the rainwater to the root of the plant. Moreover, the density of areoles and spines, the height and orientation of areole knobs determines the self-shadowing performance of a cactus. On the other hand, the spiral curvature radius and its speed of encircling the aerodynamic performance thus the self-air conditioning of the cactus body. Therefore form and water collection is interwoven into each other in the form of a cactus. Hence, transcoding cactus provides both geometrical derivations and functional goals for the generation of architectural products. It shall be noted that within the scope of this thesis, the case study will not aim to illustrate end-products of transcoding but the process of transcoding, since it is regarded as the main determinant for establishing similitude of behavior. Consequently, the research shall be reviewed considering the modeling process, which is shaped through computational modes of thinking and mediums.

4.1.1. Analyzing And Detecting The Common Properties Of Cacti

4.1.1.1 The major formal elements of Cacti Body

In this study, the main intelligence and knowledge of cactus plants to be transcoded for architecture is regarded as the associative function of form as water collecting, self-shadowing, and self-air conditioning. Thus, the parameters are explored and determined

[174] Ibid. p. 30.

within the goal of proposing and revealing relationships/ dependencies between this function and form. It is considered that transcoding this knowledge of cactus, will lead to sustainable architectural solutions with performative capacity. In this manner, the channel-like spiral geometry of cactus body can imply for rainwater collection and air circulation around a building, when the morphogenetic process belonging to the cactus is modeled and executed for architectural products.

Designating constituents and parameters of a model is not limited within the initial phases of modeling. As opposed to a linear development, the cyclic becoming process of modeling allows the discovery progression throughout the model construction. The initial parameters, which have been defined in the first attempts, may have alterations in their active positions in the model; or new parameters may be introduced that have been discovered as crucial and decisive in the generative system. In this manner, the model evolves from an abstract system towards a complex and dynamic one within the redefinitions and insertions of parameters.

From a general overview, the distinguishing property of cactus species can be considered as their sections, which determine and emerge the water-collecting, self-shading, and air flow performance of the form. The longitudinal section prefigures an idea about the overall global form, whereas the transversal section expresses the form of the cactus more specifically. It can be analyzed that the transversal section derives from polygonal geometry, while the longitudinal sections are the conclusion of growth basing on scale differences. Cut at several distinct levels, the transversal section of a cactus type preserves its geometry with alterations in its magnitude and rotation angle. The longitudinal section, on the other hand, has the identical outline at any section plane crossing from the central axis. The polygonal derivation of the transversal section determines the location of the areoles (nodes of spines) at its corners, whereas the edges of the polygon set the recessed structure of the section, which forms the waterways when it is connected continuously with other levels of sections with a rotation angle. Within this interpretation, the overall form can be regarded as the outcome of a specific transversal section’s configuration, which assemblies other sections under a scale and rotation factor.

When analysis of cactus plants are developed within this resolution, these parameters and assembly rules can be observed to be existing in almost any cactus type. The polygonal section ranges from triangles, squares, pentagons, hexagons, octagons to poly-gons, which share the function of determining the location of areoles and spines. Through simple scaling and rotating operations, the specific polygonal section happens to be structuring the global form and the settlement of areoles on the global form. Hence, a similar configuration can be

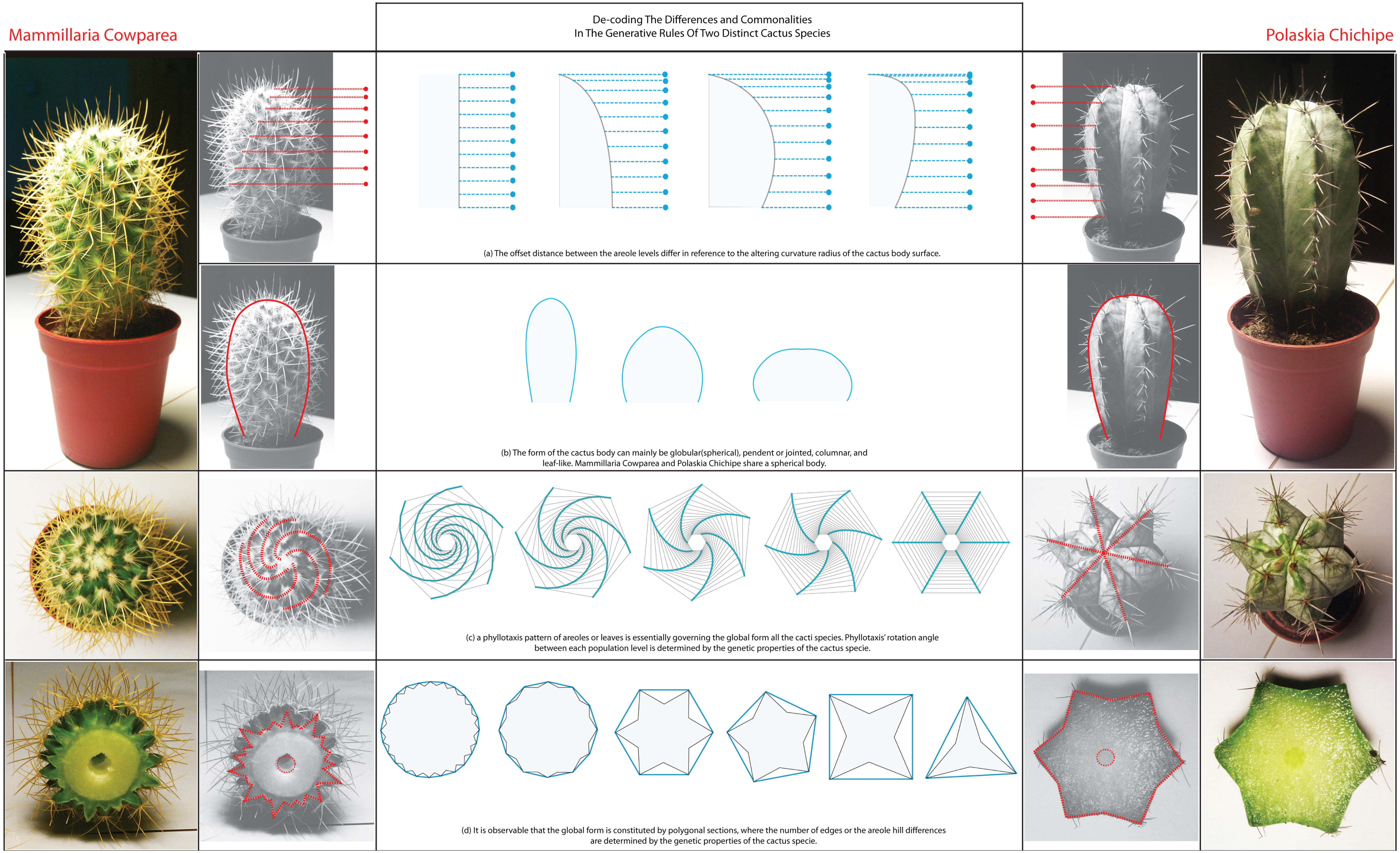

Figure 4.3 Formal analysis of Mammillaria Cowparea and Polaskia Chichipe

observed in pinecones, sunflowers, or fractal broccoli. Fibonacci series, golden section spirals have been investigated in the field of mathematics to explain such phenomena of phyllotaxis. Nevertheless, computation can provide more simpler and yet ductile explanations of such phenomena by defining its generative process through basic transformation operations such as scaling, moving, and rotating.

4.1.1.2. The common performative behaviors of The Cactus

Kolarevic declares that contemporary architecture is going through a shift from appearances to processes, in the studies focusing on performative behavior. He argues that "the role of the architects and engineers is less to predict, pre-program, or represent the building's performances than it is to instigate, embed, diversify, and multiply their effects in material and in time."[175] In this respect, rather than aiming or predicting an end product, the architect should develop the generative process so prosperous that it will cover, express, and generate a wide range of possibilities for sustainable and adaptable buildings. Thus, the transcoded generative process will have the capacity to emerge a multiplicity in outcomes as a consequence of the alterations in the system parameters. Hence, the process is accepted as the main determinant of the architectural performative behavior. Thus, the parameters nourishing the morphogenetic principles of the cactus shall be examined in order to obtain a comprehensive transcoding process.

In order to construct a unitary generative mechanism, which will constitute the transcoding model of different cacti species, two distinct cactus types will be compared. One of them will be the Mammillaria Cowparea that possesses individual units of areole hills and their double spiral organization throughout the body. The other will be the Polaskia Chichipe, where the areole hills are rather continuously integrated as vertical ribs. These two cactus species share the same natural habitat, Mexico.[176] However, they perform different responds to specific environmental conditions in consequence of the difference in their genetic codes, and thus form. Regardless of their formal disparities, almost all types of cacti have the capability of high adaptation towards their challenging environment. In this thesis, the adaptive performances of cacti will be mainly discussed under three topics, which can be counted as self-shading, water collecting and storing, and self-conditioning properties in sequence. In

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[175] Branko Kolarevic. "Towards the Performative in Architecture." p. 211.

[176] Rod Preston-Mafham. *Cacti: The Illustrated Dictionary*. Portland: Timber Press, 1991.

other words, cactus' self-protection and reaction towards the environmental conditions such as sunlight, rain and humidity, and wind will be tackled.

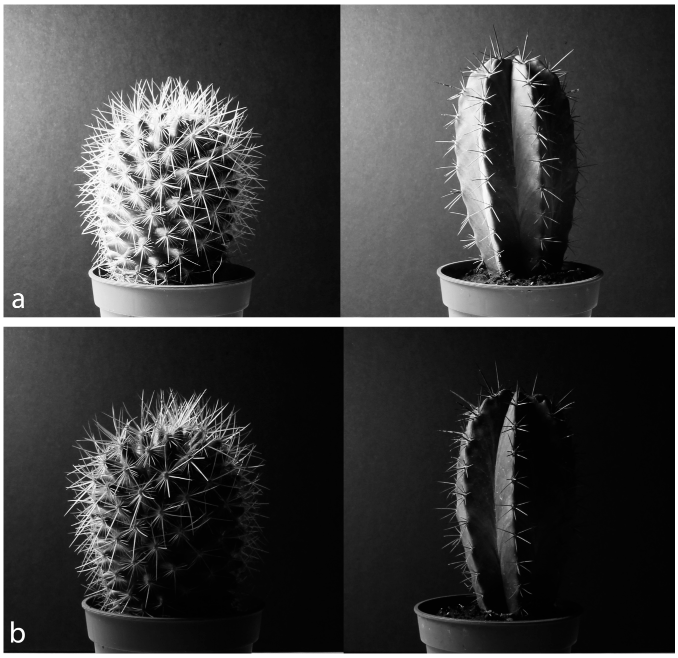

Figure 4.4 Mammillaria Cowparea and Polaskia Chichipe self-shading performance analysis: (a) high density luminance, (b) low density luminance. [Experiment and photos by the author]

When we analyze the behavior of two cactus forms under the same sunlight exposure and angle, it is observable that Mammillaria Cowparea affords diffuse distribution of light and shade on its body.(Figure 4.4) The angular organization in vertical alignment allows areoles to equally access sunlight, while the recession in each areole unit provides the capacity of distributed shading. On the other hand, the straight vertical ribs of Polaskia Chichipe cause the clear contrast of light and shade in different surface areas of the body. One surface of a vertical rib is totally exposed to sunlight, whereas the opposite surface stays completely under shadow. The difference in the cactus performances with sunlight can be related with the angular and non-angular vertical alignment of areole hills. If this dependency is transcoded to architecture, it may refer to distinct types of buildings. For example; with the angular parameters of Mamillaria Cowparea, the building body can provide identical sunlight in most of the inner spaces. Thus, this type of form implies an architectural program, where there are functions with identical light requirements. On the contrary, Polaskia Chichipe's parameters imply an architectural program, where the functions are in contradiction in terms of their requirements for sun and shadow.

The rotational self-organization of areoles in vertical alignment establishes a continuity of spirals around the body. The global distribution of areoles in Mammillaria Cowparea forms surrounding spiral channels as a conclusion of this rotation between levels. On the other hand, the areoles in Polaskia Chichipe are organized without any rotation. Thus, their collection on the global form generates straight vertical rib-like channels. In this respect, the rainwater and humidity drops are directly canalized to the ground in Polaskia Chichipe, whereas in Mammillaria Cowparea the water follows the twist of spiral channels. Therefore, it can be projected that Mammillaria Cowparea gathers water not only from its ground but also through its skin, as the rainwater travels throughout the body under the control of spiral channels. Correspondingly, when the parameters of Mammillaria Cowparea are applied in the transcoding model, it can conjure up an architectural solution where the rainwater is gathered and stored at all the levels. On the other hand, Polaskia Chichipe draws another schema, where the rainwater is directed to and stored in an underground water tank. It is known that most of cacti including Mammillaria Cowparea and Polaskia Chichipe store huge amounts of water in their body, when compared with other plants. However, it can be declared that there is a slight difference between Mammillaria Cowparea and Polaskia Chichipe as well: one has the tendency for absorbing water mostly through its skin, and the other from the ground through its roots.

Moreover, the organization of areole hills, and the channels that they form in between presents the cactus a performativity under wind forces and airflow. The spiral or rib form of the channels manages the wind and airflow around a cactus, such that the occurring air stream regulates the climate and ambiance surrounding the cactus body. In order to analyze and understand the cacti behavior under such circumstances, an experiment on Mammillaria Cowparea and Polaskia Chichipe has been conducted within the scope of this thesis. In the experiment, a set up similar to a wind tunnel has been constructed, such that the cactus is exposed to a continuous airflow with white fume. As it can be seen in Figure 4.5 that Mammillaria Cowaparea allows the air flow roll all around its body and conveys the air to its back. On the contrary, Polaskia Chichipe's solid ribs do not allow the air pass from the sides of the cactus body. But the ribs collect the air that hits on the body and pours the collected air from the channel's top.

When the airflow is sent with high velocity, it can be observed that the cactus forms maintain their performative behavior within consistency. Mammillaria Cowparea again conveys air through all around its channels to its back, such that wind gaps don't occur around the body. In the case of Polaskia Chichipe, the airflow is again directed through the channels towards the top of the body, while a part of the wind is reflected from the surfaces of ribs. These behaviors belonging to two distinct forms of cactus can invoke an architectural insight about how a building can find its form within the limitations and requirements of environmental conditions. For example, the sent airflow sweeps through Mammillaria Cowparea's spirals. This performance can become the reason to prefer similar parameters for generating architectural forms that needs to adapt hot climates or wind forces. Nevertheless, Polaskia Chichipe is more collective rather than conductive. Its form may create additional and unbalanced building loads and lead to structural instabilities. Therefore, because of this inadequate performance with wind forces, Polaskia Chichipe's formal parameters may be preferred to generate built terrains or considerably low-rise buildings.

Figure 4.5 Mammillaria Cowparea and Polaskia Chichipe fluid dynamics performance analysis: (a) low velocity, (b) high velocity air flow. [Experiment and photos by the author]

Throughout these analyses, it has been revealed that cactus form is the critical determinant of various performative activities. Parameters, which identify the mentioned alterations in cactus performance under specific environmental conditions, can be counted as the associative self-organization and distribution of areole hills on the global form, and their extrusion depths. The variations in these parameters have generated distinct cactus species, as well as different responds and adaptations towards identical environmental factors. Correspondingly, the introduction of analogous parameters and dependencies in the transcoding model will be crucial, when it is intended to establish similar passive performances in architectural design.

4.1.2. Phyllotaxis: The Generative Mechanism of Form and Performance/Efficiency in Cactus

4.1.2.1. Defining Phyllotaxis In Different Scales of Natural Organizations

In various types of cactus plants, it can be observed that the form of cactus body is closely inter-related with and determinant of the cactus performance. The major agents for establishing the performative behaviors of cacti species can be listed as:

- The organization and distribution of areoles on the global form,

- The density and length of spines,

- The depth of areole hills,

- The spiral or rib-like channels, which the areole hills frame.

In other words, the efficiency of behaviors such as rainwater collection, self-shadowing, and self air conditioning do essentially derive from the areole arrangement. In cacti, there is a tendency for spiral growth formation of areoles. This spiral formation can bring forth both the differences and resemblances in an extensive variety of cactus plants, if it is parameterized and generated from lower level agents and determinants. However, a broader group of plants embrace the spiral growth and arrangement of leaves, seeds and spines, which has been named as *phyllotaxis* (leaf ordering) by Charles Bonnet in 1754.[177]

In the framework of plants that grow from a stem, phyllotaxis refers to the spiral pattern that governs the leaf growth and configuration. The phyllotaxis pattern has been classified under three main topics: spiral, distichous, and whorled.[178](Figure 4.6) If the angle between each consecutive leaf equals to the angle of 137.5^0 when observed from top, the phyllotaxis is named as *spiral*. If the angle equals to 90^0 between each consecutive leaf generations, the phyllotaxis is named as distichous. When each foliation level has two pairing leaves mirroring each other with the angle of 180^0, the phyllotaxis is named as whorled. The pattern of phyllotaxis has been interpreted as the efficient solution of nature. In spiral phyllotaxis, the leaf arrangement is such that none of the growing leaves are locating on top of a leaf at a

[177] Phillip Ball. *Nature's Patterns: A Tapestry in Three Parts: Shapes*. New York: Oxford University Press. 2009. p. 226.

[178] Ibid. pp. 226-227.

lower level. In this manner, the accessibility to sun-light and thus efficiency of photosynthesis has been provided.[179]

Figure 4.6 The phyllotaxis classifications of leaf arrangements: (a) spiral, (b) distichous, (c) whorled.

Philip Ball. *Nature's Patterns: A Tapestry in Three Parts: Shapes*. New York: Oxford University Press. 2009. p. 227.

However, phyllotaxis does not only refer to leaf growth and organization, but it is also refers to the spiral pattern and configuration of seeds. In this respect, the intention is to pack seeds in a specific surface area with optimal spacing, or to spread the seeds towards numerous distinct orientations such that the possibility of proliferation and survival is mounted up.[180] Besides in seed packing, it can be recognized that the spiral pattern is constituted from the collocation of two spirals, which grow towards opposite directions. The double spiral of phyllotaxis in seed packing can be recognized in the florets of a sunflower head and daisy, the leaflets of pine and spruce cones. It should be reminded that there is an order and underlying geometry governing the seed organizations in most of the flowers, fruits and

[179] About the efficiency of photosynthesis in accessibility to Sun light:
Jay Kappraff. "Growth in Plants: A Study in Number." In Forma, Vol:19, 2004. p. 346.

Daniela Brites, Fernando Valladares. "Implications of opposite phyllotaxis for light interception efficiency of Mediterranean woody plants"

Daniela Brites, Fernando Valladares. "Leaf phyllotaxis: Does it really affect light capture?"

Available from: http://www.springerlink.com/

[180] Jay Kappraff. "Growth in Plants: A Study in Number." p. 340.

vegetables.[181] Apple, bean, and pomegranate seeds are some familiar examples of such order, which we have acknowledged from our everyday experiences. Yet in the framework of this thesis, solely the spiral pattern of seeds is focused as an extension of phyllotaxis. Other than seed arrangement; flowers, vegetables and fruits have the double spiral growth pattern in their florets, petals, or rinds as well. It can be illustrated by romanesco cauliflower, rind of pineapples, globe artichoke heads, layered cabbage leaves, the order of rose and chrysanthemum petals.

Similarly in cacti, a phyllotactic double spiral governs the array of areoles and spines around cactus' whole body, which is of vital importance for self-protection from environmental factors. Nonetheless, the properties and parameters of the spiral organization of areoles differ extensively in the family of cacti. The number of spiral ribs, the angle and scale ratio between consecutive levels fluctuate depending on the genetic code of the cactus. In addition to that, the temporary alterations in weather conditions and drought index may also cause deviations in the continuity of the complete spiral form. Thus, it is not easy to classify cacti species according to the spiral phyllotactic formations of areoles under specific numerical angles. The angles, which the spirals are composed of, are emanating from a range of values rather than being equal to a static number. Yet, it is possible to draw a "shared body plan", which may model a large proportion of the cactus family within a common generative mechanism.

4.1.2.2. Modeling Phyllotaxis Within Distinct Literacies and Theoretical Frameworks

The parabolic spiral order in most of the plants is being analyzed for over a hundred year. Several source texts claim that from Ancient Egyptians and Greek geometers to thinkers like Leonardo Fibonacci, Leonardo da Vinci, Kepler, D'Arcy Thompson, and Wolfram have studied the spiral order in plants.[182] Eventually, the explanatory model of phyllotaxis has altered through time, as the modeling tools and literacy shifted. Ultimately, the phyllotaxis models evolved to be more precise, three-dimensional, flexible, and dynamic.

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[181] Observations from "Non-design" assignment studies as a part of Basic Design courses at Istanbul Bilgi University in 2010-2011 academic year.

[182] Phillip Ball. *Nature's Patterns: A Tapestry in Three Parts: Shapes*. New York: Oxford University Press. 2009.

A brief history of Phylotaxis can be found from: http://www.math.smith.edu/phyllo/OldFiles/History/historynoroll.html (Last resumed at 22.01.2012.)

The first approaches to understand phyllotaxis did depend on proportional scaling and angular rotation in two-dimensional space. Archimedean Spiral and Fermat's Spiral were interpreted as the equivalents of the phyllotactic spiral. The algorithmic installations or numerical notions were not familiar to Ancient Greeks, thus Fermat's Spiral was defined through basic operations of geometric transformations such as rotating, scaling, and copying. As it was explained in Chapter 2, proportional constructions acted as mediatory devices to understand natural objects and draw inferences for the artificial/man-made objects. Accordingly, the phyllotactic spiral and its generative principles were considered as basing on proportional growth of radius (distance from a central reference point) at each specified angular interval.

Cook claims that through history, humankind has been in the search for a curve definition that would elucidate the similarities in the curves of nature, which could be observed in many objects from seashells to leaf outlines.[183] Perhaps, the most familiar and famous approach of all times has been the Golden Spiral and the Golden Section, of which underlying geometry is comparably simpler to explain and comprehend. The underlying generative geometry of Golden Spiral is defined through the collocation of squares, which increase in size following a logical order and intend to imitate the growth sequence in nature. The algorithmic process of growth refers to the previous squares such that the edge length of a square is equal to the sum of the edge lengths of previous two generated squares. Then, in the procedure of establishing the Golden Spiral, the control points of the curve is matched with the corners of the underlying squares. Fibonacci sequence and the growth process of its numbers correspond with the algorithmic logic of the Golden Spiral. The number series of 1,1,2,3,5,8,13,34 are both the sequential elements of Fibonacci numbers, and the edge length proportions between the Golden Spiral's underlying squares. The ratio between consecutive number of this series equals to a certain value that is named as the Golden Section. Nevertheless, it can be realized that Golden Section, Golden Spiral and Fibonacci numbers directly refer to one type of spiral, where the numbers are defined and not changeable. In this respect, specific numbers are appreciated more than the mathematical and geometrical relations. Thus, it can be concluded that the generative process of the logarithmic spiral, which all these constructions designate, has been underemphasized through this explanatory model.

The geometrical and mathematical explanations of phyllotaxis have stayed as two-dimensional, until Van Iterson put forth the idea of the cylindrical model. In the cylindrical model, the volume that is enveloped with the phyllotactic pattern is abstracted as a regular

183 Theodore A. Cook. *The Curves of Life*. London: Constable and Company, 1914.

cylinder, whereas the units of the pattern are interpreted as tangent circles. The simplification and abstraction of the three-dimensional form to regular geometrical elements enables the development of the phyllotactic surface on two-dimensional space. Erickson in 1983, Prusinkiewicz and Lindenmayer in 1990 established their phyllotaxis studies by developing Van Iterson's cylindrical model concept. Common to all these models, the phyllotaxis pattern is defined by two or more interlocking helices. In this respect, each packed circle on the surface is an interlocking point of the parastiches[184] of these two types of helices.

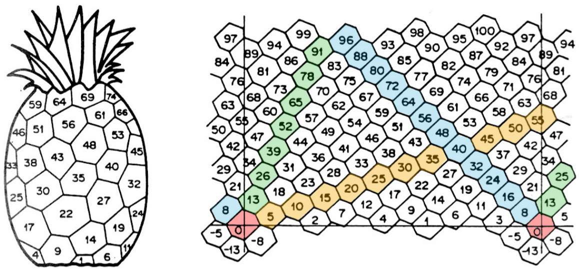

Figure 4.7 Coxeter's model of numerical labeling to explain phyllotaxis.

Jay Kappraff. "Growth in Plants: A Study in Number." In Forma, Vol:19, 2004.

Similarly, Coxeter analyzes phyllotactic pattern on the rind of pineapples in a cylindrical model.(Figure 4.7) In his cylindrical model, the globoid structure of pineapple body is abstracted as a semi-infinite cylinder.[185] When this cylinder is unfolded, the rind stalks turns into a planar hexagonal tiling that facilitates mathematical and geometrical analysis within two-dimensional reference system. In this model, the stalks are labeled with numbers, which illustrate the chronological order of stalks' generation sequence. The lower hexagonal stalk is settled as the zero point, where the imaginary coordinate system locates its origin point. The X-axis of the coordinate system acts as a reference line in order to determine the labeling numbers in a chronological order. As the distance between each stalk center and X-axis increases, the labeled numbers are amplified. After the labeling process, it can be realized that there is a pattern of numbers in the adjacent cells of spirals. The numerical difference between neighboring hexagons is in repetition throughout a spiral route. This numerical order implicates that there is an order of growth in pineapples.

[184] Parastich refers to one brach of phyllotactic spiral. In a phyllotactic organizations, there are arrays of usually three types of parastiches.

[185] Jay Kappraff. "Growth in Plants: A Study in Number." pp. 336-337.

From a general outlook to the unfolded hexagonal pattern of pineapple rind, it is observed that there are three main spiral routes. For example, the 'zero' stalk indicates the initial point for three spiral continuities towards distinct directions. The phyllotactic patterns can be named after the three parastiches: the array number of each parastich to travel the 360^o. In the case of Coxeter pineapple, it is a 5-8-13 phyllotaxis: numbers that correspond to the neighboring cells of the 'zero' stalk. It can be concluded that as the growth pattern alters according to the genetic code or environmental conditions of specie, another phyllotactic and numeric pattern will be regenerated through this principle mechanism.

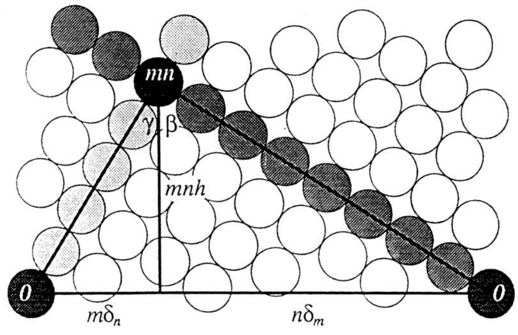

Figure 4.8 Erickson's model of unfolded cylindrical surface to explain phyllotaxis [186]

Phillip Ball. Nature's Patterns: A Tapestry in Three Parts: Shapes. New York: Oxford University Press. 2009.

On the other hand, Erickson intends to generate the global phyllotactic pattern from local interactions.(Figure 4.8) He defines the relations of one circle with its neighbors, the double helices, and the global form. Therefore, Erickson departs from the numerical understanding of phyllotaxis. He develops a relational, algorithmic, and parametric approach that will elucidate a common motor diagram that will generate distinct phyllotactic patterns. In Erickson's model, a parastiche triangle constitutes the underlying geometry. The two distinctive parastiche orders are referred to as *m, n*. The triangles' two lower vertices equal to the initial interlocking point (0) of the double helices, while the third vertice corresponds with the circle, where double helices interlock for the second time (mn). Erickson constructs an algorithmic model, where the relations of circle-packing pattern are identified with *vertical and horizontal displacement*, and *divergence angle* between consequent tangent circles on a helix route (let it be *m*). As the values of *displacement* and *divergence angle* alter, the circle-packing pattern is modified. Therefore, the tangency relationship between

[186] J. E. Dale, F. L. Milthorpe. *The Growth and Functioning of Leaves*. Cambridge Univ. Press, New York: 2011.

circles and the steepness of phyllotaxis helices are redefined in a bottom-up manner (from local to global). Hence, once the generative algorithm is established, juggling with the values of variables can produce a wide range of phyllotaxis variations.

Prusinkiewicz and Lindenmayer have a similar understanding of phyllotaxis as a mechanical process rather than numerical. In pursuit of the cylindrical model, Prusinkiewicz and Lindenmayer have interpreted phyllotactic pattern as a circle-packing problem on a cylinder surface.[187] They have built up an L-system algorithm and proposed a specified formula, which associates the *divergence angle*, *vertical displacement*, *population sequence*, and *point coordinates* on the cylinder surface all together.(Figure 4.9) Moreover, they have modeled this explanatory mechanical system in computational medium and literacy. Thereby, Prusinkiewicz and Lindenmayer have opened up a computational insight for the phyllotactic pattern generation studies. In their model, the fundamental algorithm that gives rise to the L-system has been:

"$\varphi = n * \alpha, \qquad r = const, \qquad H = h * n$" [188]

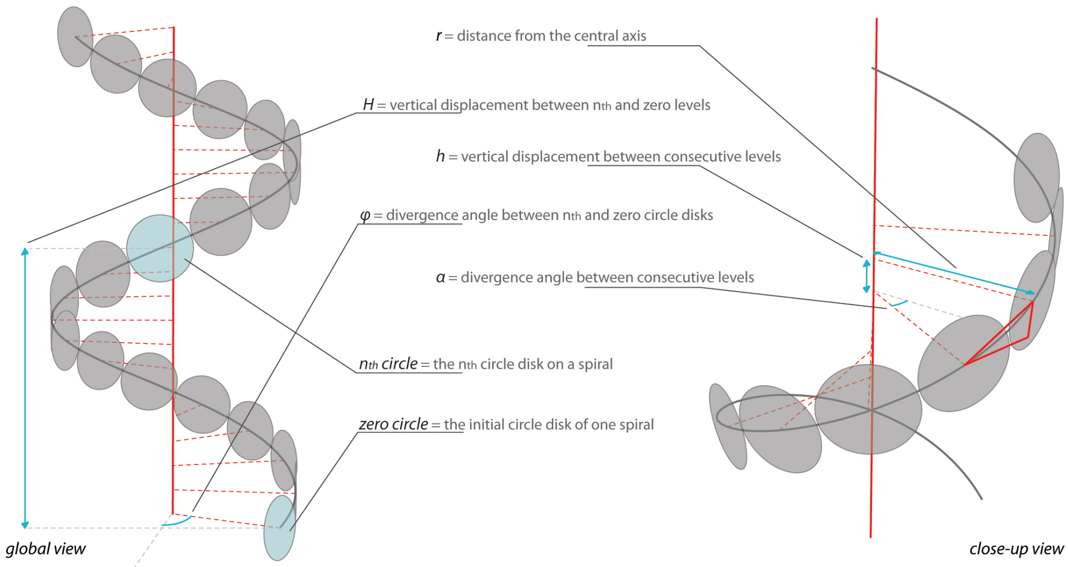

Figure 4.9 Prusinkiewicz and Lindenmayer's parametric model of phyllotaxis. [Author's diagrammatic illustrations] [189]

[187] Przemyslaw Prusinkiewicz, Aristid Lindenmayer. *The Algorithmic Beauty of Plants(The Virtual Laboratory)*. Springer, 1996. p. 110.
PDF File of the book can be found at: http://algorithmicbotany.org/papers/abop/abop.lowquality.pdf (Last resumed at 05.01.2012)

[188] Ibid. p. 109.

[189] The illustrations are derived from Prusinkiewicz and Lindenmayer's explanations in:
Ibid.

It can be realized that all the possible *n*th circles have the same vertical distance with the consecutive circle according to Prusinkiewicz and Lindenmayer's formula. There is a uniform pattern of helices on the cylindrical phyllotaxis, where there is a constant horizontal distance to the central axis at all levels. Each circle disk is identical and identically related with its neighboring cells and global form. In this thesis, the computational resolution of cactus form and phyllotaxis has emerged within parallelity to Prusinkiewicz and Lindenmayer's formula. However, the cactus model introduces more flexible relationships between the phyllotaxis points, while it considers the global form as a parabolic volume rather than a cylinder.

The common deficiencies of these models can be interpreted as the differentiation between circle disks' sizes, the radius of phyllotactic spiral, and the in-repetitiveness in global form as the manifestation of alteration through growth and time. However, phyllotaxis is the record of time at the same time. While the smaller units refer to the recently produced young leaves, seeds, petals or areoles; the bigger units refer to the elements from previous generations. Moreover, variation in the size of units enables the three-dimensionality of phyllotaxis pattern covering globular volumes. In order words, phyllotaxis establishes a pattern for tessellating the double-curved surfaces. Consequently the transcoding model, which will be illustrated in detail in the next chapter, will intend to integrate this property of phyllotaxis to the generative system. The tree-dimensionality and double-curved property on phyllotactic surfaces will be recognized as an associated outcome of the phyllotaxis generative mechanism. Thus in this thesis, form and phyllotaxis pattern will be interpreted as interrelated, associated, dependant on and mutually generating each other, rather than an overall form as a previously defined geometrical input, which has been simplified as a planar surfaces or cylinders in the previous models.

In this thesis, the transcoding model has been intended to illuminate the unity and divergence in cactus plants. Thus, a more comprehensive mechanism of phyllotaxis has been developed that would generate form, areole configuration, and performance rising from one complete and inclusive computational system. This comprehensive mechanism that is discovered to be common in most of the species has been illustrated in Figure 4.10 The polygonal transversal section of the cactus, its sequential growth, their level distance increments through generations and the common divergence angle between consequent generations have been observed in the analysis of cactus form. While associating these properties with each other in an interrelated manner, the generative system of cactus form, phyllotaxis, and performance have been discovered to be corresponding and sustaining each other. Once the relations and operations in such a system are defined, it is possible to explain and generate an extensive variety of cacti. Hence, the algorithmic relations and operations in the system directly depend on the modeling literacy, and modeling media. In this thesis, the transcoding computational model is constructed through Monkey Script Editor, of which limits and constraints, potential and capabilities have been determinant. In the next chapter, the encoding process of computational cactus model within Monkey Script Editor will be elucidated more in detail.

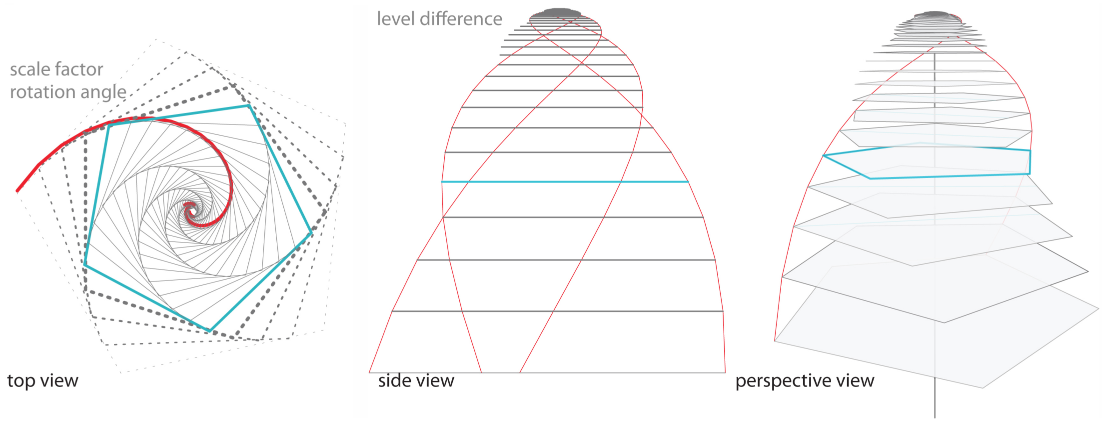

Figure 4.10 The 'shared body plan' of the cactus family. A schematic representation of parameters, operations, relations and the generative set-up at a high level of abstraction.

4.1.3. A Preliminary Survey For Discovering Cactus Features From Previous Approaches That Interpret Nature In Built Environment

There have been several architectural designs, of which their properties share some features common to cactus species. For instance, Mary Axe Tower of Norman Foster can be examined for the building's performative behavior that can be regarded as common to the cactus plants. The building provides its inner air circulation and heat balance through the spiral configuration of gallery spaces between different levels. The uniform shift of the floor endings at each level provides a continuous spiral that initiates from the ground floor and continues till the top of the building.(Figure 4.11) In this manner, the spiral gallery spaces provide air circulation as airshafts, while at the same time heat is distribution and equilibrium established throughout the building. In this way, the building's energy consumption is reduced by half.[190] Moreover, the spiral configuration of the gallery space provides visual connections and social interactions between distinct floors. Additionally, the gallery enables light to penetrate to the deeper parts of the building, which have mentionable

[190] Branko Kolarevic. "Towards the Performative in Architecture." *Performative Architecture Beyond Instrumentality*. Edited by Branko Kolarevic, Ali M. Malkawi. New York: Spon Press, 2005. p. 211.

distance to the façade. Regarding these aspects of the Mary Axe Tower, the cactus plant can be analyzed as sharing properties and functions such as the uniform rotation principle of levels, which lead to a spiral configuration in the waterways/atria and promote the fluid/hydro-dynamic movement of water/air in and around the body.

The Fourth Phase of Eden Project design by Nicholas Grimshaw (2003) can be counted as another architectural design that shares common properties with cactus. The building's roof structure has been generated through a logarithmic system using computer aided design tools.[191] The form of the roof structure is a shell generated from phyllotaxis configuration, which can be observed to exist in the form of cactus plants as well. The roof also embraces a solid-void pattern similar to the aggregation of leaves in a tree. Thereby, the roof provides shade and light uniformly distributed in the inner space. In such a manner, the building roof becomes a second skin that acts as a solution for establishing air circulation and heat control. Similarly in cactus plants, the phyllotaxis organization of areoles comprises a second skin to the plant, which provides protection and shade.

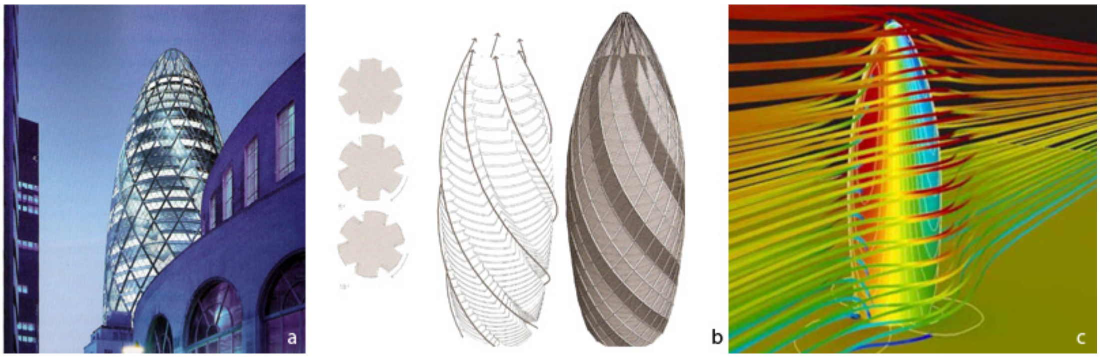

Figure 4.11 Mary Axe Tower by Norman Foster (2004, London), and its interpretation for transferring natural form's air flow performance into architecture: (a) A photo of the building (b) A graphic illustration of the building's air flow control through the interior floor layers, (c) The CFD analysis of the buildings external form.

Performative Architecture Beyond Instrumentality. Edited by Branko Kolarevic, Ali M. Malkawi. New York: Spon Press, 2005.

The Function of Ornament. Edited by Farshid Moussavi, Michael Kubo. Barcelona: Actar, 2006.

Marianne Feiberger. "Perfect Buildings: The Maths of Modern Architecture". http://plus.maths.org/issue42/features/foster/index.html. Last resumed in 03.03.2012.

[191] Andrew Whalley. "Product and Process: Performance-based Architecture." *Performative Architecture Beyond Instrumentality*. Edited by Branko Kolarevic, Ali M. Malkawi. New York: Spon Press, 2005. p. 37.

Studies on phyllotaxis (branching structure of leaves) show that the configuration of leaves around the stem involves a rule of rotation between respective leaves. In this arrangement, the growth and form generation arises such that there is utmost surface area of leaves facing the sun in order to establish more efficient photosynthesis and to shade on the plant body ground at the same time. In a computational model developed by Biothing and SOM Architects, the "rotation with scale" principle of phyllotaxis has been examined regarding its potentials for architectural form generation.(Figure 4.12) The computational model has been constructed through L-system rules and structures.[192] As a result, the branching system has been set up with several parameters and variables including 'growth ratio', 'generations', and 'rotation angle'. Additionally, the rules, relations, dependencies in the generative system are regarded as a variable called 'rule string', through which modifications would lead alterations in the global outcome of the model. Thus, the computational model of branching as a glass-box allows interference of the architect at any stage of the generative system, such that the generated outcome can be developed towards more precise and implicative solutions for architecture.

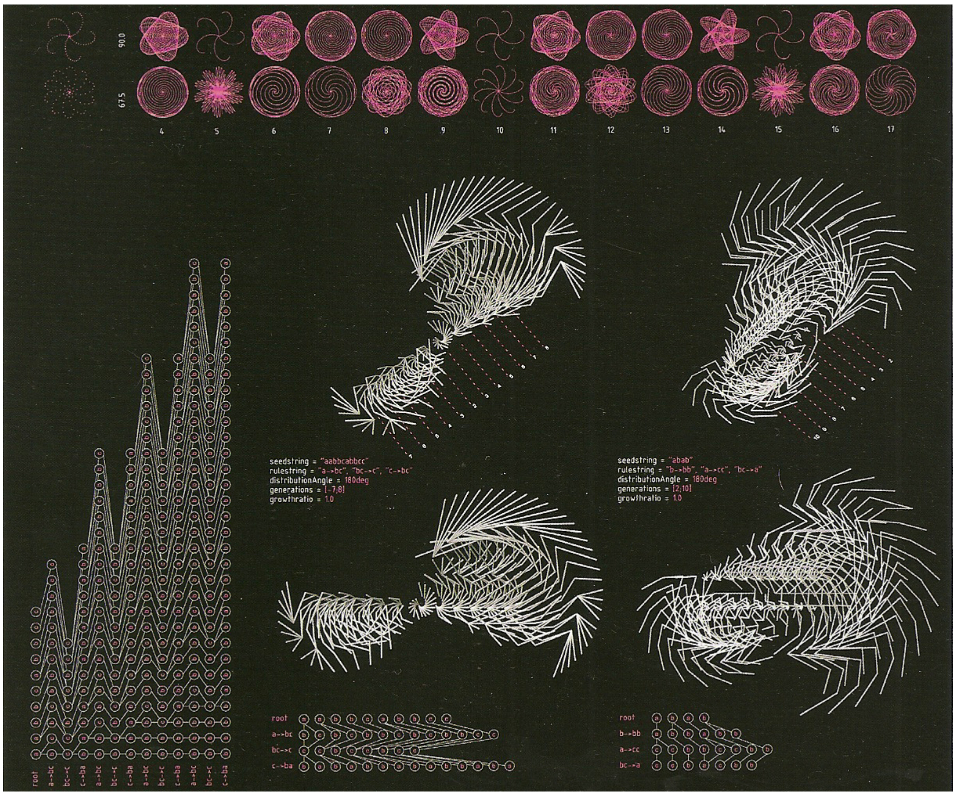

Figure 4.12 Emerging spiral organizations as outcomes of the L-system computational model of Phyllotaxis by Biothing and SOM Architects.

Collective Intelligence in Design: Architectural Design. p. 24.

[192] Alisa Andrasek. "Continuum: A Self-Engineering Creature-Culture." *Collective Intelligence in Design: Architectural Design*. Vol 76, No 5, 2006. p. 24.

In the documentary named ‘Human Planet: Deserts-Life in the Furnace’, it is reported that the inhabitants of the Chilian Atacama Desert have developed another interpretation of cactus for advancing their own artificial water collectors.[193] It is recorded that the inhabitants have observed that the cactus plants of the area were capable of collecting the moisture in the air by their net like spines, even though there is no rain. The inhabitants analyzed that these specific cactus types were covered with fury glycan nets, which was interpreted as the main catalyst of the water collection. Following this information, they built up surfaces made of nets that would resemble the behavior of the glycan hair and collect the moisture in the air. Similarly, Jason Vollen and Kelly Winn developed a sustainable façade design called EcoCeramic Masonry for Brickstainable Design Competition, where innovative solutions for brick usage are promoted.(Figure 4.13) Their façade system has been inspired from the self-shading and thermoregulating surface articulation of barrel cactuses and form of termite mounds.[194] In other words, their proposal redesigned brick units in such that that they would mimic the performative behavior of cactus skin and areoles, which control the airflow and shade rate around the body.

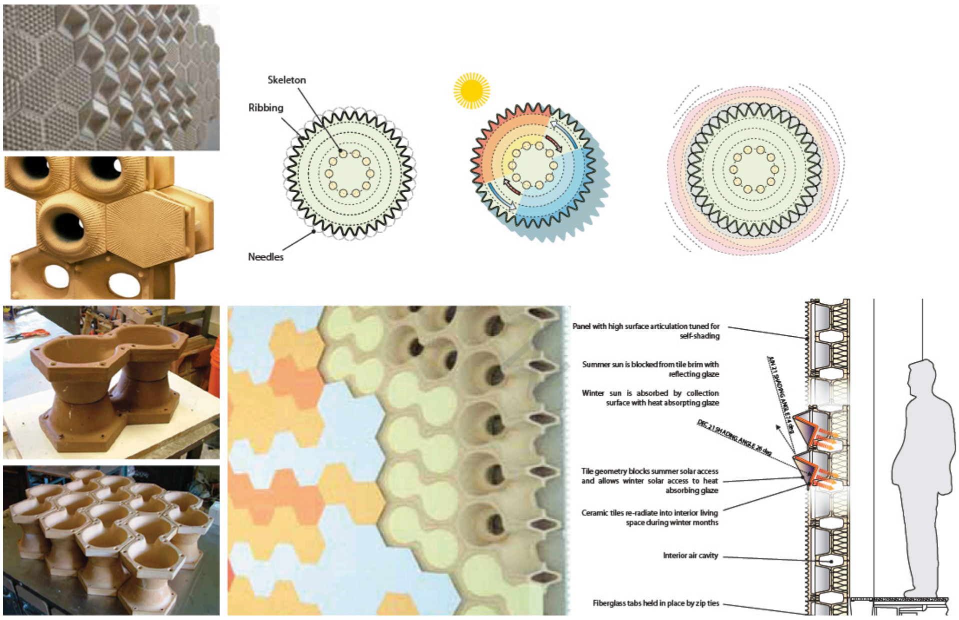

Figure 4.13 The EcoCeramic Masonry System, competition entry by Jason Vollen and Kelly Winn.

The presentation board can be found at http://www.brickstainable.com/current-winners/technical-design.html. Last resumed in 08.01.2012.

[193] BBC Documentary. "Human Planet. Deserts: life in the furnace."

[194] The presentation board can be found at http://www.brickstainable.com/current-winners/technical-design.html. Last resumed in 08.01.2012.

In 2007, another cactus study has been realized at the Architechural Association as the diploma project of Andres Harris and Omid Kamvari. In this research, the morphological development of a cactus in relation to its performative behavior has been modeled and evaluated in computational media.[195] Harris and Kamvari have constructed a parametric computational model of cactus that would generate a three-dimensional Nurbs model of cacti species.(Figure 4.14) Thus, the performative behaviors of cactus under various environmental and structural conditions have been tested on the outcomes of this generative model. Within this approach, the model became the interface to understand and learn the generative dependencies and relations between form and performance of cactus.

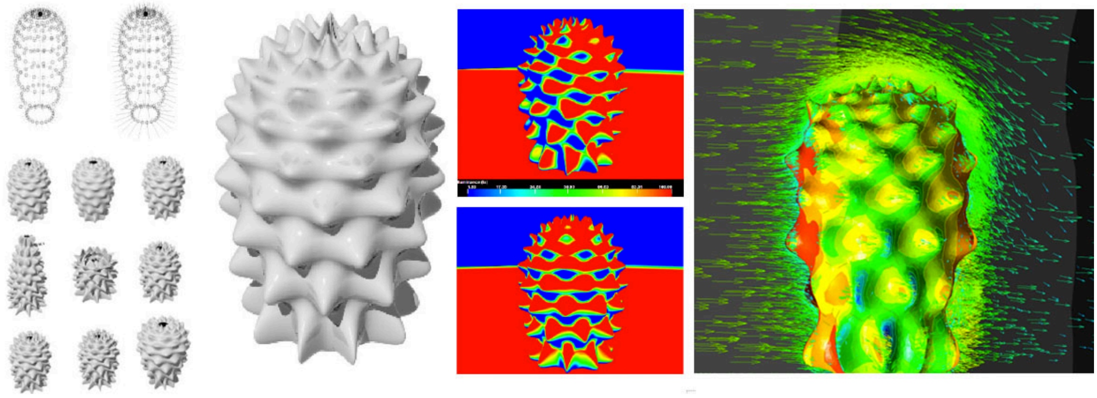

Figure 4.14 AA Emtech Diploma Project of Andres Harris and Omid Kamvari.

http://www.aaschool.ac.uk/PORTFOLIO/projectreview.php?title=Project%20Review%202007&url=www.aaschool.ac.uk/aadvd/ Last Resumed at 23.11.2011.

Common to these projects, they have their own way of learning from nature. The extracted type of knowledge, and its modeling/systematizing determines the architectural solutions and outcomes. While in the design of MaryAxe Tower performativity, sustainability and behavior of the architectural product is aimed, in Eden Project the integrity of structural and formal aspects is in the spotlight. the Chilian interpretation stays as an inspiration, whereas Jason Vollen and Kelly Winn follow a more methodological study for mimicking cactus skin behavior. On the other hand, Andres Harris and Omid Kamvari organize a computational process in order to learn about the cactus behavior under environmental conditions such as luminance and airflow. Therefore, the artificial product is evolved to be a functional device that operates similar to a cactus with its water collecting capacity; however there is no systematic 'transcode's for transferring natural knowledge to the artificial. Thus, the

[195] Visuals explaining the project can be found from:
http://www.aaschool.ac.uk/PORTFOLIO/projectreview.php?title=Project%20Review%202007&url=www.aaschool.ac.uk/aadvd/ Last Resumed at 23.11.2011.

provisions about the architectural implications of a knowledge transfer, orientates the whole process of modeling and thus transcoding.

4.2. Modeling Literacy: Scripting

As it was explained in the previous chapter, computer acts as a meta-interface, within which the user is capable of reaching other interfaces such as programs. Through this attitude, the program becomes another interface for the user to interact in order to construct models within a specified language and structure. In this context, computers embed nested interfaces. As the user gets involved with a more deeply nested interface, he/she needs to communicate in a more particular and restricted language/ structure. At the same time, he/she gains more control, awareness about the process system while he/she gains authority on the model.

For architects, scripting is such kind of a multi-layered language. The scripting program works in the limitations and potentials of the associate program. In the following case inquiry on constructing a transcoding computational model, scripting will be the tool and interface of the modeler. Monkey Script Editor, which is a plug-in of Rhinoceros 3D Modeling program, is selected for carrying out the studies on modeling cactus for architecture. It shall be mentioned that there are vast amount of programs, based on script or not, which could develop a computational model of a cactus. Moreover, each architect can develop a different model within the same interface. Hence, the computational model that will be illustrated in this thesis shall be regarded as one of the many probable computational models of the cactus, which has its own limitations, potentials, interpretations, and structure of generative system. For this reason, the model generated here will be referred as *a* computational model amongst many that are constructed or probable to be constructed.

One of the main key points for choosing Monkey Script Editor has been the explicit character of scripting that provides an exposure of the general system structure and the local operations, agents. Through such an interface, the user is both the constructor/ director and the learning apprentice of the computational model. Secondly, Rhionoscript works in association with the Rhinoceros screen such that the user can define the variables and instantly evaluate the outcome from its visual simulation. Another determinant in choosing Rhinosript has been the author's acquaintance with the program. Yet, it is crucial to mention that the primary intention of the study doesn't arise from or base on the practice of scripting but the process of transcoding.

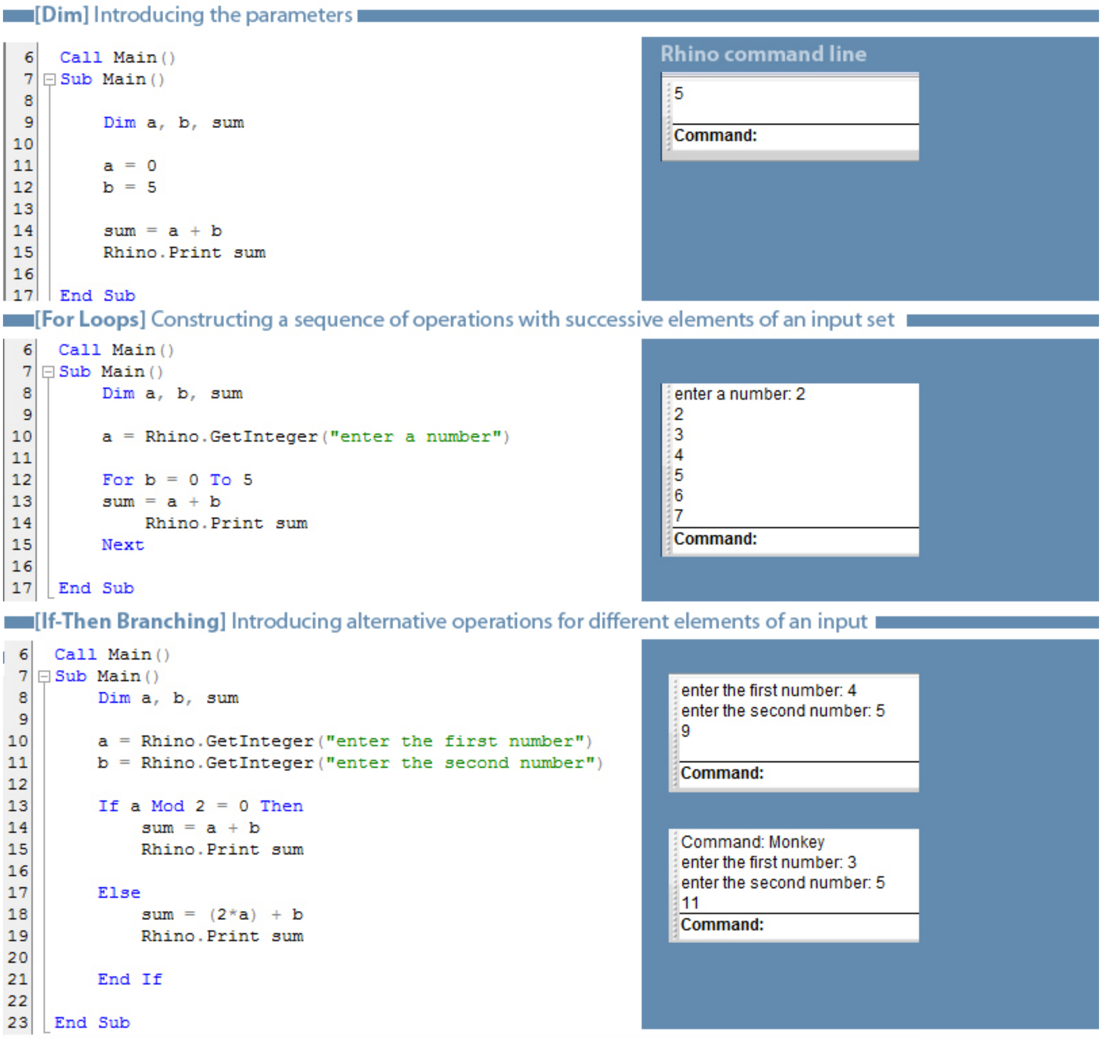

Figure 4.15 A basic summation operation in rhino script evolves to be more complex as *for loops* and *if-then* branches are introduced. [Illustrated by the author]The interaction of the script program with Rhinoceros is illustrated at the right-hand side. Since the summation operation doesn't include visual elements, the command line screens the outcome of the system.

Through building a computational system, the process is as important as the outcome. Whenever a process is defined, the output of the operation becomes an input for the following operation. In this manner, the modeler constructs a complete system that will operate as the local outputs turn to be inputs for the sequential operation. Thus, in a scripting practice, the modeler needs to enunciate the input, parameters, variables and output, which will be defined but not identified. In Rhinoscript, the definition operation is established through '*dim*' phrases. The two main syntax expressions belonging to Rhinoscript structure can be counted as '*for loop*'s and '*if-then*' branches. For loops execute an operation for every member of the input set respectively. In other words, each time a '*for loop*' revolve, another sequential member of the set becomes the input of the specified operation. *'If-else'* constructions are mostly built in '*for loop*'s. In this manner, while the '*for loop*' counts each member of the input set, '*if-then*' braches collect members as subsets that are processed through different operations. Thus, by structuring these syntactic phrases, the model gets more complex as well as more precise. The thesis inquiry on transcoding will be based on mainly these basic syntactic constructions, and simple VisualBasics operations.

In the next chapter, an inquiry on transcoding nature into architecture through constructing computational models will be demonstrated. In this study, it will be observed that scripting is the active constituent of the *observe-analyze-generate-test* cycles. Through these cycles of learning, the modeler observes simulation of the constructed model in Rhinoceros screen; analyzes its fallacies, deficiencies, and inadequacies. Later, he/she detects the source of the problem or realizes an uncovered potential and rewrites some parts of the model. At this point, he/she may introduce new *for loop, if-then,* or *dim* structures in order to develop the model towards a more accurate transcoding. Thus, the generate-test cycle, then, can be regarded as another analog *for loop* that involves the modeler as the active agent in the evolution of the model. In the next chapter, through the process of transcoding, the initial model with a high level of abstraction will be observed to be evolving towards a dynamic and complex system, which is comprehensive enough to manage and express both the cactus and the architectural design.

CHAPTER 5

TRANSCODING II: EN-CODING THE NATURAL AND ARCHITECTURAL PROCESS IN A GENERATIVE SYSTEM

Through the process of *constructing* computational models of nature, *transcoding* the knowledge of nature to architecture, and *becoming* of the global information processing; nature is continuously revisited, architectural form generation process is recurrently modified and the architect is simultaneously learning and rediscovering the conjunction of architecture, computation and nature, while she/he examines the application of cactus performance knowledge in architectural products. Modeling is a multi-layered process, which operates through continuous loops that constitutes feedbacks and forwards to develop the model towards a more accurate, consistent and complete system. Clive Dym argues that modeling is established throughout the continuum of "model-validate-verify-improve-predict" loops, which constitute the iterative aspect of modeling process.[196] Correspondingly, Herbert Simon has proposed "generate-test" cycles, which lead the progression and design of computational constructions.[197] In this thesis, Simon's expression will be elaborated as *observe-analyze-generate-test* loops, which conduct the transcoding process that aims to build computational models of nature for architecture. Each time this loop revolves, the model evolves from an abstract insight towards a more precise, more operative, and more complex generative system. Thus, from this perspective the dynamic process of modeling constitutes an area of research by itself.

It shall be added that the process of modeling through computational thinking and media is intertwined with the modeled process of the research object. In such practice, the architect as the modeler experiences/ conducts multi-dimensional feedback loops, as he/she reconfigures the computational resolution of both natural and architectural organizations. Hence, he/she

[196] Clive L. Dym. *Principles of Mathematical Modeling*. 2nd Edition. Elsevier Adacemic Press, 2004[First published in 1980].pp. 7-8.

[197] Herbert A. Simon. *The Sciences of the Artificial*. Third Edition. Cambridge, MA: The MIT Press, 1996. First published in 1968. p. 74.

needs to draw a descriptive and normative model at the same time. In this respect, the architect holds a dual position in the modeling process. First, he/she has a descriptive attitude towards the research object, since there is a search for discovering and defining a shared generative process – an abstract body plan. Secondly, he/she has a directive position in the transcoding procedure, while the order and rules are designated and assigned within an aim for establishing prospective architectural products. In this chapter, this dual position of the architect will be examined such that the natural and architectural inferences of the transcoding model will be explicated, while regarding the modeling process as an ever-ending iterative loop. Although, in this thesis the decoding and encoding processes have been scrutinized under distinct chapters, it shall be reminded that decoding and encoding are actually strictly knotted throughout the process of modeling.

5.1. Encoding The Generative Process of Cactus Within Monkey Script Editor

As it was mentioned before, the cactus family is highly populated. In this study, a section of cactus species are researched in the aim for uncovering and designating their common geometric derivations, which will then act as the parameters of the computational model. Throughout this search, the difference between several cactus types is examined in a constructive manner to derive a shared body plan – a common generative process, where alterations can flourish versatility and vicissitude within one model. Hence, within this potential of generating and expressing distinct outcomes, architectural possibilities are enunciated in the model. In this way, the computational model embraces the 'transcode's which transfer the information extracted and discovered in the natural organization to the architectural design process. The generative and parametric supremacy of model provides the potential of establishing difference and similarity in the outcomes. Moreover, the model defines both the process and the processed. Thus, determining the parameters and basic rules of the reasearch object is the building stone of the overall transcoding/modeling/designing process.

In this respect, variety and 'perpetual novelty' are major considerations for designating constituents of a cactus such that through the transcoding procedure these parameters can raise up variety in the architectural outcomes. John Holland defines perpetual novelty as:

> "[...]A small number of rules or laws can generate systems of surprising complexity. Moreover, this complexity is not just a complexity of random patterns. [...]In addition, the systems are animated –*dynamic*; they change over time. Though the laws are invariant, the things they govern change.[...]The rules or laws *generate* the complexity, and the ever-

> changing flux of patterns that follows leads to *perpetual novelty* and emergence."[198]

Thus, in reference to Holland's description, 'perpetual novelty' expresses the dynamic, complex, flexible, and contingent character of a model and generative process, which will rise up a populated set of possible outcomes.

Within their generative principles, simple initials and rules, computational models include a capacity to evolve towards a complex dynamic system, where several outcomes of one model can be generated and tested. In this manner, the architect as the modeler may communicate with the object of investigation through the simplicity of computational method and medium, and still can give rise to complex process of architectural design. Manuel DeLanda proposes that "if evolved architectural structures are to enjoy the same degree of combinatorial productivity as biological ones they must also begin with an adequate diagram, an 'abstract building' corresponding the 'abstract vertebrate'."[199] From this perspective, the initial step of constructing computational models is simplifying the generative process of research object with a level of abstraction. In our case, the properties of the cactus shall be interpreted and reshaped at a level of simplification and abstraction. Through this approach, the transcoded knowledge may instigate the form generation of architectural process within the same level of abstraction. Thus, the model will produce outcomes that imply open-ended solutions in architecture. These open-ended alternatives, then, can be developed by evolving the model towards a more complex, dynamic and precise one by inserting parameters, or realizing alterations in the operations.

The construction of a computational model initiates with a high level of abstraction and simplification. The abstract expressions aim to give an idea about the generative system, which carry the potential of being a 'shared body plan' of the cactus family.[200] Moreover, within the scope of this study, the computational model of the cactus is considered as the shared generative mechanism of architectural design in correspondence. Through its becoming, the model will be evaluated by the modeler in terms of its fit for both the investigated object of nature (cactus) and the possible architectural inferences. Thus, throughout the becoming of the model, generate-test cycles nourish the evolution of the model from a highly abstract and simplified system towards a complex and dynamic one.

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[198] John H. Holland. *Emergence: From Chaos to Order*. New York: Oxford, 2000. p. 4.

[199] 'Shared body plan' term is borrowed from Manuel DeLanda. "Delueze and the Use of the Genetic Algorithm in Architecture." in *Phylogenesis: foa's ark*. Edited by Foreign Office Architects. Barcelona: Actar, 2004. p. 526.

[200] *Ibid*. p. 528.

In the practice of transcoding cactus and architecture, the decoding and encoding of the process is essential. It shall be noted that the selection of parameters, variables, operations constituting the generative system is the consequence of the theoretical framework of modeling insight, the expressive medium and tools of the modeling literacy as well as the constructive interpretation of the modeler. Thus, the decoding process executed in this thesis shall be regarded as one of the numerous interpretations for a computational resolution of the cactus.

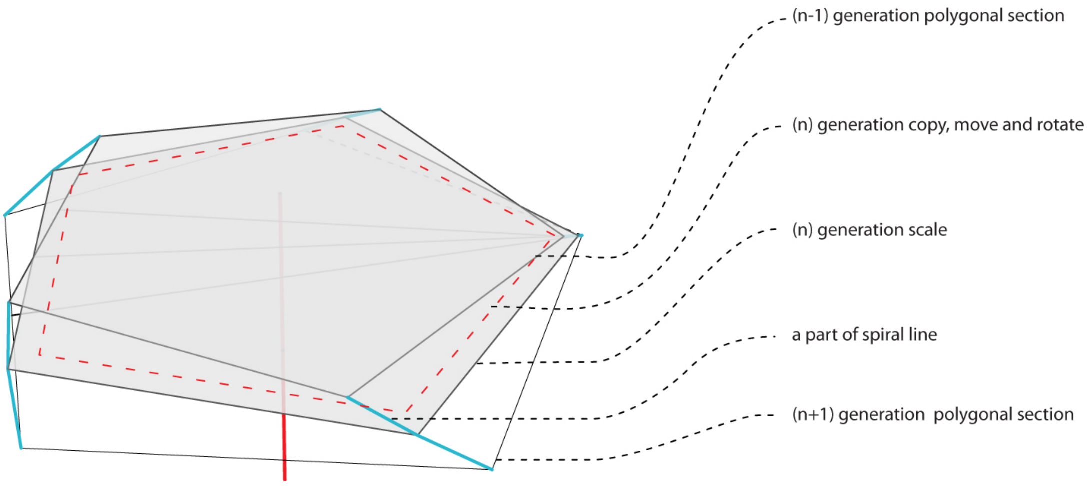

Figure 5.1 An abstract working model illustrating local interactions between components of transversal sections. [Developed by the author]

In the observations on the cactus, it has been analyzed that in all the cactus types the areole arrangement follows phyllotactic rules within a dependency on the transversal section outline. The multiple transversal sections belonging to cactus shares common geometrical derivations and polygonal outlines within an alteration in scale/magnitude and rotation/orientation. Hence, the computational resolution of such relationships and dependencies can be obtained through maneuvering basic transformation operations in the section geometry.(Figure 5.1) Consequently, these operations would generate and organize the configuration of transversal sections, which will be determinant on the areole arrangement as well as the overall form. In this respect, a computational system proposes an integrated understanding of several properties such as overall form, areole arrangement, channels geometry emerging from local interactions and parameters. After numerous observe-analyze-generate-test loops, the user defined parameters and constants values of the Cactus script has been designated as follows:

coreGeo = the core closed polyline geometry

stepNum = the number of layers that are to be generated

Ang = the divergence angle between each consecutive layer (0-180)

LevelDifMin = the initial level difference

LevelFactor = the multiplier of level difference between each concecutive layer

Hillheight = the height of areole hill

ScaleFactorConstant = the multiplier indicating the scaling between each consecutive layer.

= (1.1, 1.1, 1.1)

The user defined parameters and initials are augmented in the transcoding computational model of cacti, since this provides a larger set of possible states and probable unprecedented outcomes. In this manner, the perpetual novelty of the model has been increased; the model becomes more flexible and comprehensive while the user gains more control on the generated overall form through defining the parameters of local interactions. For structuring the local interactions between components of transversal sections, the *for loop*, which is a nested group of operations working in self-repeating cycles, is used to generate new levels of polygonal sections in reference to the previous sections at each regression. (See Appendice A for the Pseudocode of Cactus Script) In such a generative resolution, the local interactions between the agents of polygons are determining the overall form of the outcome.

It shall be noted that through constructing computational models, the working model is reshaped/modified/progressed depending on the mediums and tools the interface program presents. In our case, the evolved model includes more precise definitions about the base points of rotation and scaling operations. Moreover, the interface of Monkey Script Editor allows the modeler instantly execute the generative system and test the consistency of the system through the simulation of the generated outcome demonstrated in Rhinoceros window. Thus, besides the feedback loops and interactions in the computational model, another knowledge constitution loop revolving through the model outcome, the modeler, the interface, and the research object proceeds, resulting with a reconstruction of the model each time.

It shall be added that model and simulation are two different practices. Simulation belongs to the model or is a tool of the model; its representation or visuality may differ. Simulation is "a technique for achieving an understanding and predicting the behavior of systems".[201] In this case study, simulation is established within the collaborative operation of Monkey Script

[201] Herbert Simon. *The Sciences of The Artificial*. Massachusetts: MIT Press, 1972. p. 14.

Editor and Rhinoceros window. (The CD attachment demonstrates the communication between Monkey and Rhinoceros windows) As the script is executed, the generative process is simulated step by step. Thus, it establishes the observation phase of the '*observe-analyze-generate-test'* cycles, and provides feedback loops of learning/approving the system configuration.

It can be observed in the pseudocode in Appendice A that, the modeler both discovers (as a result of observations on the research object and generated outcome) and assigns (as a result of the potentials and limitations of the computational system) orders on the cactus plant. In this respect, the modeler follows a normative and descriptive approach throughout the process of modeling. As it was mentioned in previous chapters, Simon declares a dichotomy between normative and descriptive manners of the natural sciences such as biology and the sciences of the artificial such as engineering.[202] In this study, the dual intention of the architect as the modeler can be observed in the process of constructing computational models of the cactus and transcoding this information in architecture. While, the modeler intends to express and describe various types of a cactus in a computational system, he/she reconstructs and reshapes the model within normative concerns about the prospective transcoding process and through the constraints of the modeling literacy and representation medium.

5.2. Validation of the Model: Testing the Possible Outcomes of The Script and Their Compatibility With Cactus Species

The 'perpetual novelty' of the established Cactus Script is revealed, as the user is liberally defining and playing with the values of parameters. Besides, the interactive and associated interfaces of Monkey Script Editor and Rhinoceros provide rapid execution and simulation of the script. Therefore, the user can simultaneously test and observe the behavior and results of the model, when it operates within the given parameters. When we explore into the script's possible set of outcomes, it can be realized that the model is capable of generating a wide spectrum of cacti species including Mamillaria cowparea and Polaskia Chichipe, which are analyzed in Chapter 4. (Table1) Moreover, Table2 and Table3 approves that the model can provide other formal outcomes as well by virtue of its broad range of parametric values.

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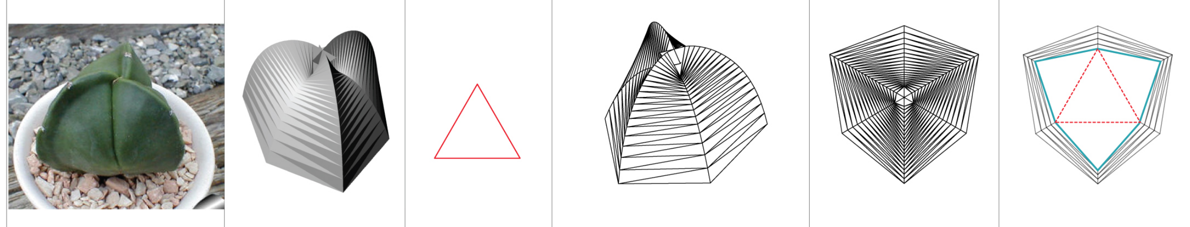
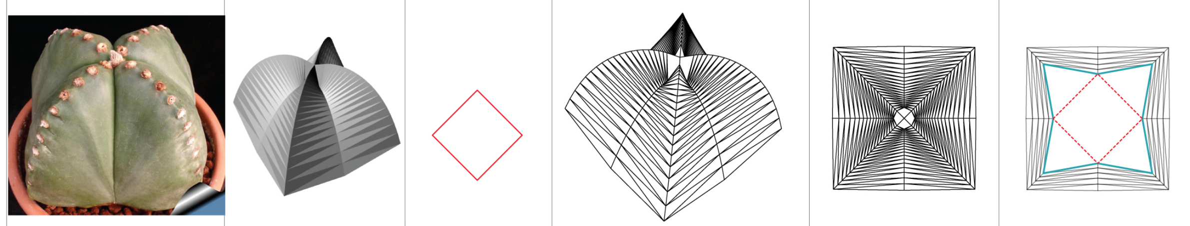
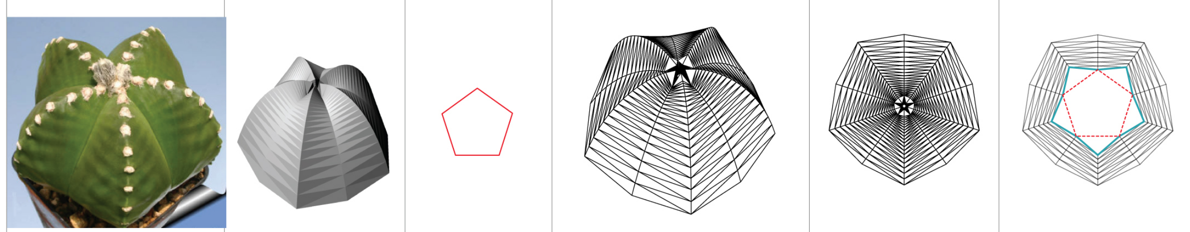
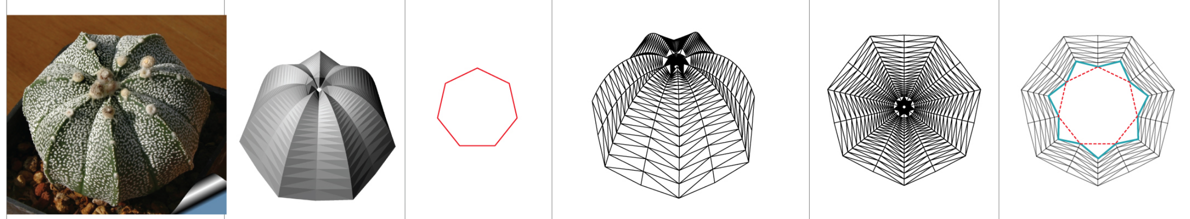
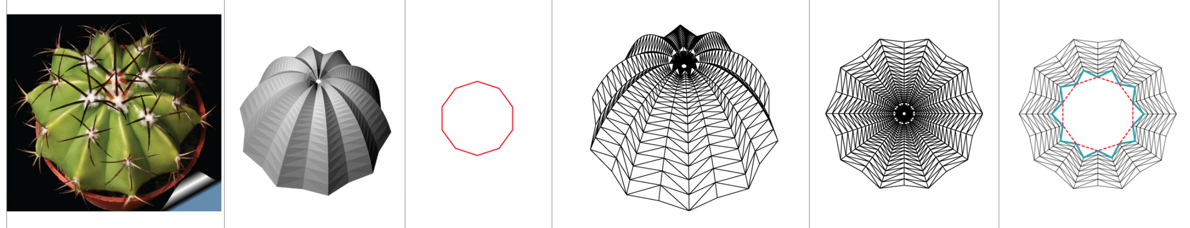
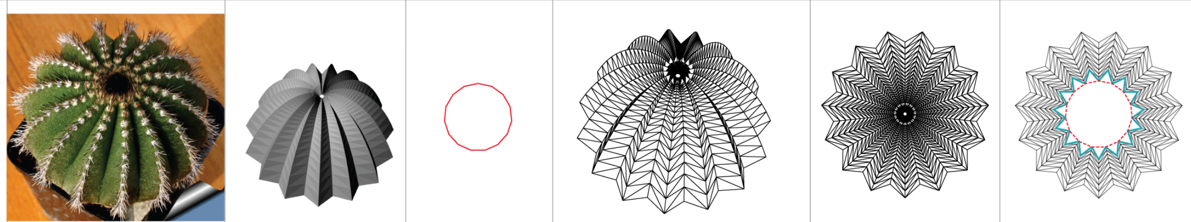
[202] *Ibid.*

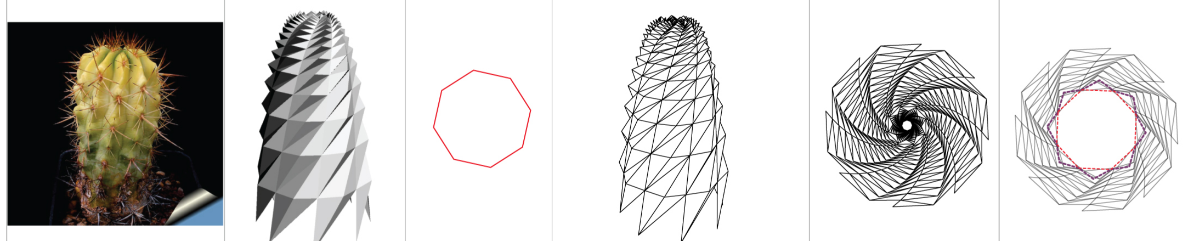
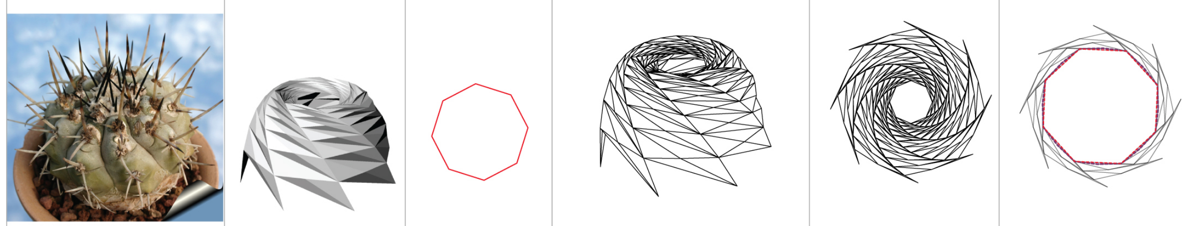
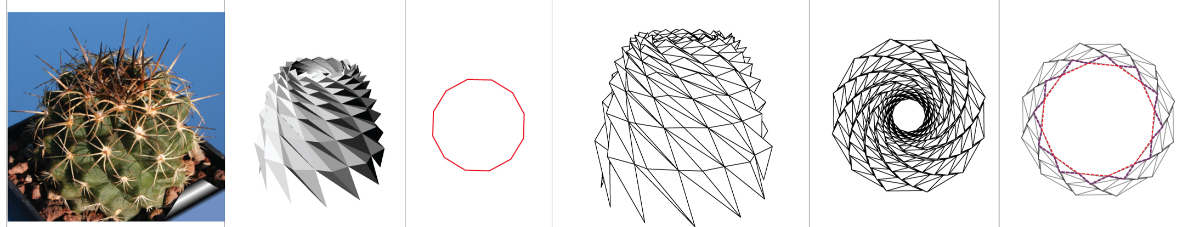
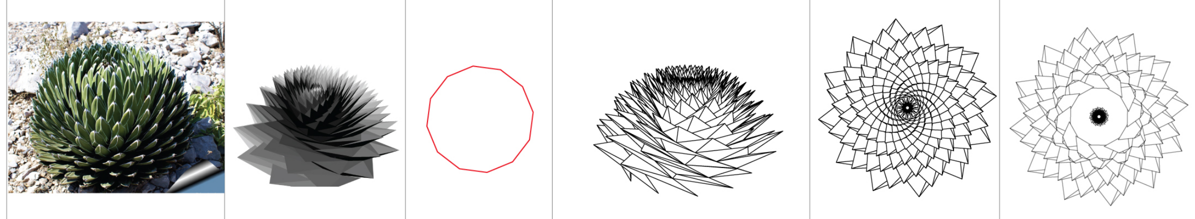
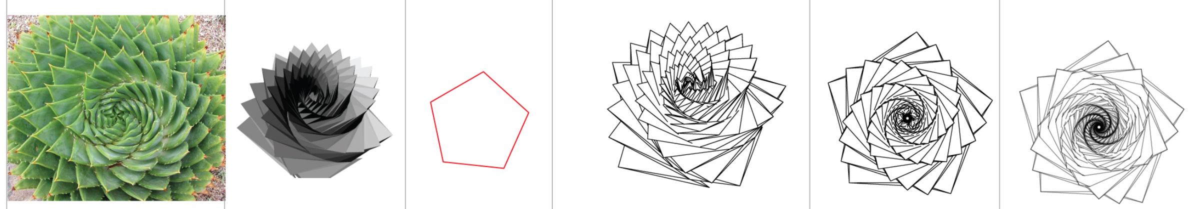
5.2.1 The Correspondence of the Model with Cacti Species

Table 5.1 Testing the Correspondence of the Script Outcomes With The Cacti Species.

NON - ANGLED CACTUS TYPES

Inputs	Cactus Photo	Digital Model Render	Initial Geometry	Script's Outcome Form (Perspective)	Script's Outcome Form (Top)	Script's Outcome Section
stepNum = 40 Ang = 0 LevelDifMin = 5 LevelFactor = 12 Hillheight = 70	 astrophytum myriostigma tricostatus		Number of Edges = 3			
stepNum = 40 Ang = 0 LevelDifMin = 5 LevelFactor = 12 Hillheight = 50	 astrophytum myriostigma quadricosta		Number of Edges = 4			
stepNum = 40 Ang = 0 LevelDifMin = 5 LevelFactor = 12 Hillheight = 30	 astrophytum myriostigma nudum		Number of Edges = 5			
stepNum = 40 Ang = 0 LevelDifMin = 5 LevelFactor = 12 Hillheight = 20	 astrophytum hybrid AS-CO		Number of Edges = 7			
stepNum = 40 Ang = 0 LevelDifMin = 5 LevelFactor = 12 Hillheight = 15	 melocactus guaricensistrico-		Number of Edges = 10			
stepNum = 40 Ang = 0 LevelDifMin = 5 LevelFactor = 12 Hillheight = 20	 uebelmannia pectinifera		Number of Edges = 15			

ANGLED CACTUS TYPES

Inputs	Cactus Photo	Digital Model Render	Initial Geometry	Script's Outcome Form (Perspective)	Script's Outcome Form (Top)	Script's Outcome Section
stepNum = 30 Ang = 5 LevelDifMin = 5 LevelFactor = 13 Hillheight = 10	 capiapoa pseudocoquimnbana		Number of Edges = 8			
stepNum = 15 Ang = 10 LevelDifMin = 10 LevelFactor = 14 Hillheight = 1	 copia cinera longispina		Number of Edges = 8			
stepNum = 17 Ang = 10 LevelDifMin = 10 LevelFactor = 14 Hillheight = 5	 copiapoa domeykoensis		Number of Edges = 12			
stepNum = 17 Ang = 20 LevelDifMin = 10 LevelFactor = 14 Hillheight = 5	 copiapoa paposoensis		Number of Edges = 12			
stepNum = 38 Ang = 20 LevelDifMin = 5 LevelFactor = 12 Hillheight = 60	 agave victoria reginae		Number of Edges = 12			
stepNum = 38 Ang = 15 LevelDifMin = 5 LevelFactor = 12 Hillheight = 70	 aloe polyphylla		Number of Edges = 5			

5.2.2. An Exploration Into the Extensive Set of Possibilities of Cactus Script

Table 5.2 Populations of the Script With Different Initial Polygonal Geometries, and Different Divergence Angles.

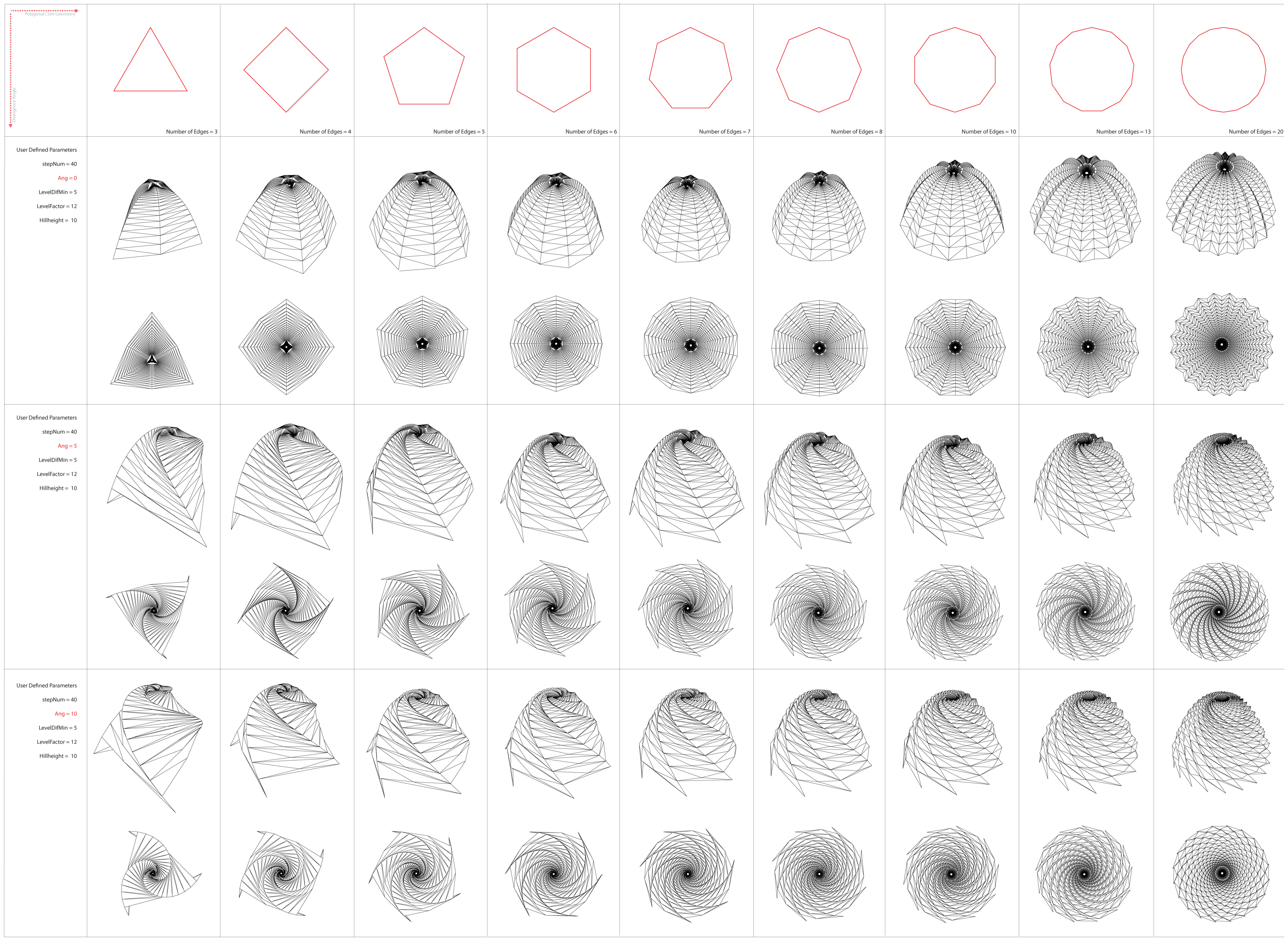
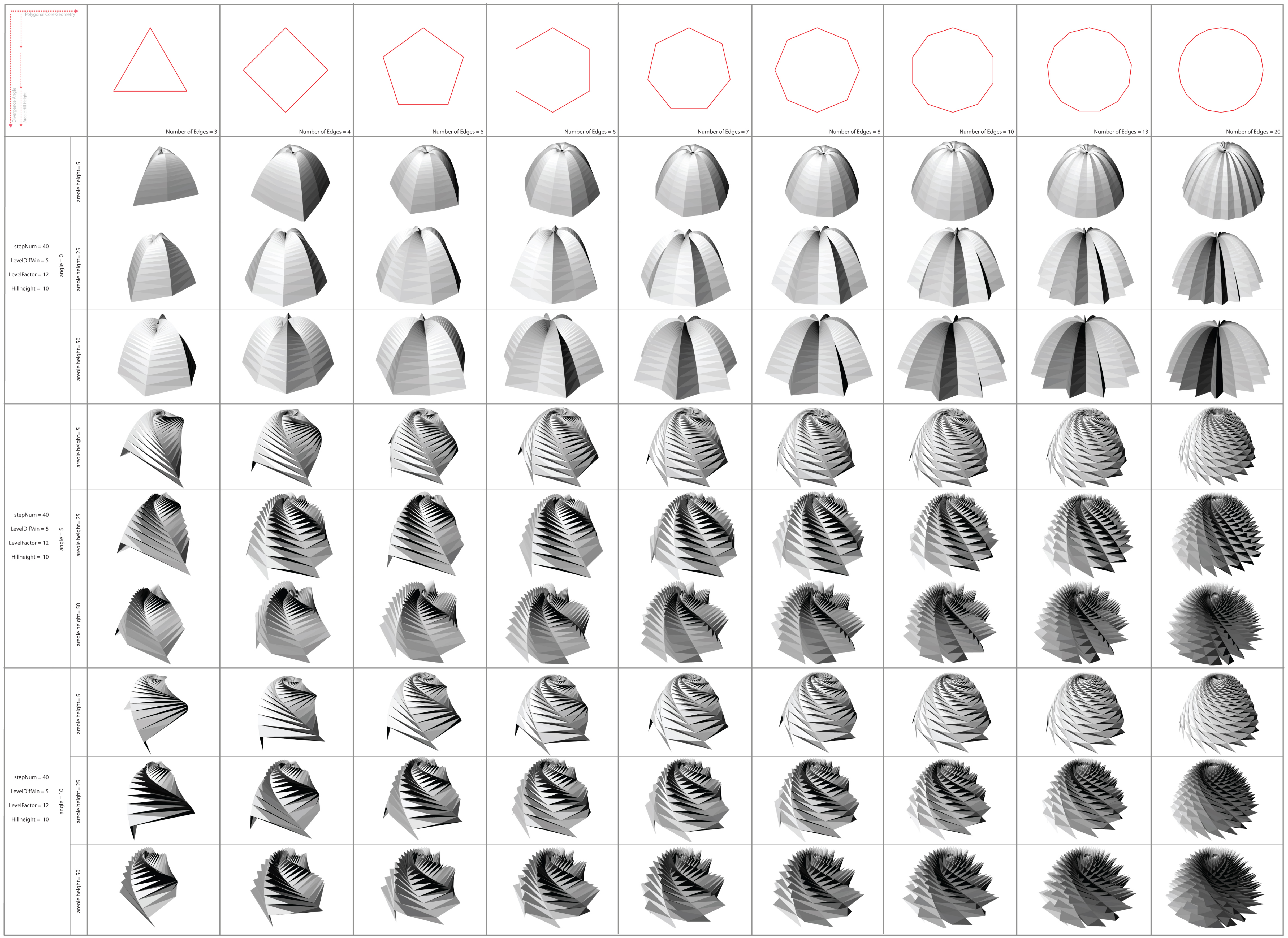


Table 5.3 Populations of the Script With Different Areole Hill Depths



5.3. Verification of the Model: Experimenting The Script For Architectural Probabilities

As it was analyzed and explained in Chapter 4, cacti species carry out performative behavior under external factors such as wind, sunlight, and water. Since the architect is the major contributor of the transcoding process from its very beginnings, it has been foreseen through the analyses that these performative activities of cacti can establish a point of departure for generating architectural products and sustainable solutions. Thus, the inseparable integrity and association of form and performance is taken as the fundamental cactus intelligence to be transcoded from nature to architecture. In this manner, the challenging environmental conditions and climatic factors would be regularized in the built environment through passive reactions.

As the architect oriented the total process of extracting the necessary and related knowledge from cactus and modeling it in a generative system, it wasn't necessary to make fundamental changes or additions in the structure of the script through the process of projecting architectural inferences. In the script, the continuous skin of cacti plants has been interpreted as triangulated plates, which would make the construction process of the architectural inference possible. Moreover, these extruded triangulations and tessellations has been scripted identically and within sequence, such that in a future architectural projection it would be possible to make openings in the pattern according to the climatic and environmental requirements of the building. (Appendice A)

Due to the performative capability of the cactus intelligence, it has been considered that this knowledge can be transcoded to architectural projects that are located in challenging climates or exposed to tough environmental factors. One of the possibilities can be listed as high-rise buildings, which need to control and regularize airflow and wind forces around its body in order to insure its structural stability. Another can be counted as built terrains, which are located on wavy landscapes and aims to control and collect rainwater. Interpreting the cactus skin as a double façade is also promising, such that it can be applied on double curved surfaces and provide protection from sun and rain, while at the same time it penetrates airflow inside the building. (Hence, the performative capabilities of several forms shall be tested through CFD (Computational fluid Dynamics) programs to test the wind and water flow, solar analysis programs to experiment the day lighting and shadowing that the global form provides. In this manner, the compatibility of a generated form can be calculated in order to find satisfycing architectural solutions.

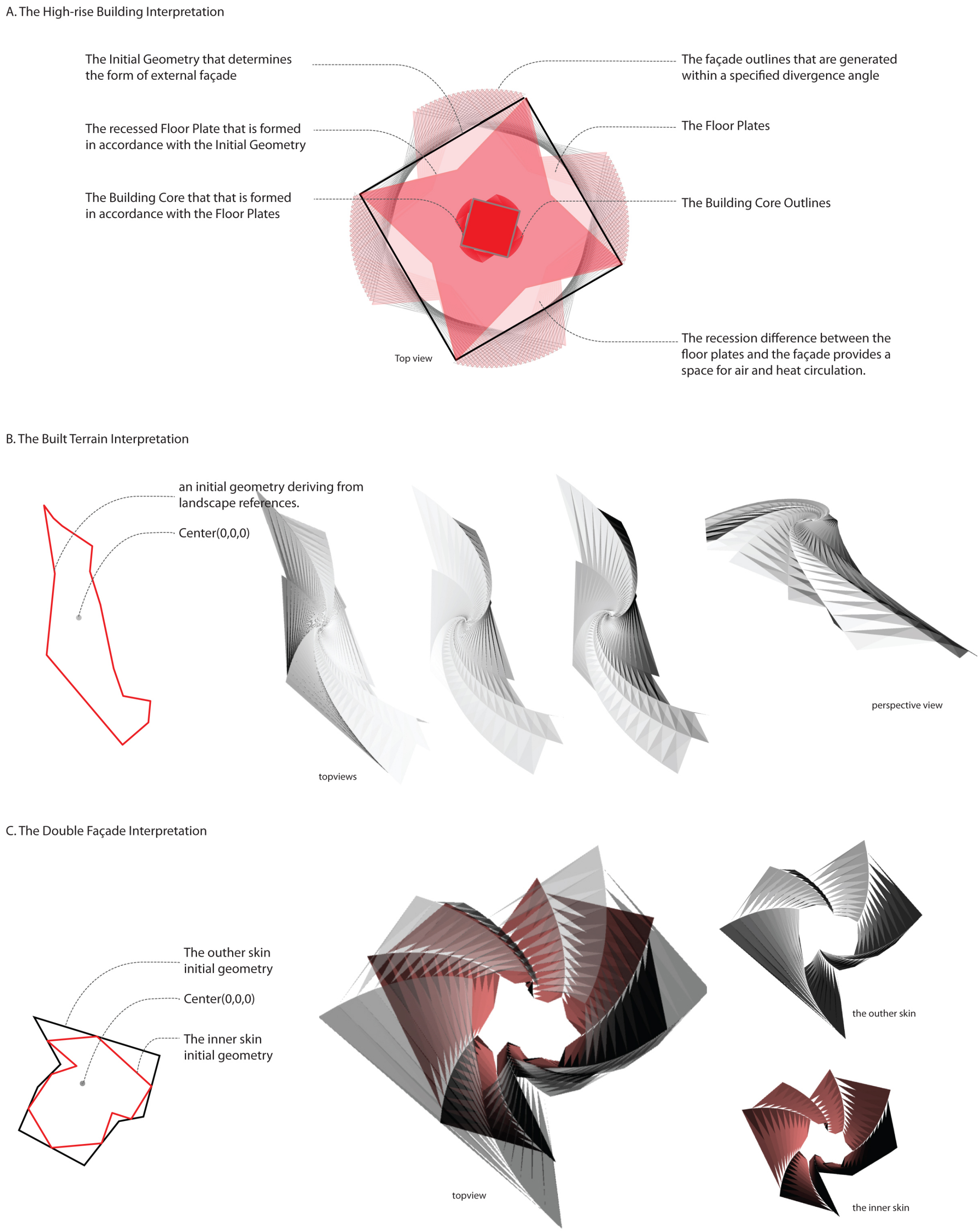
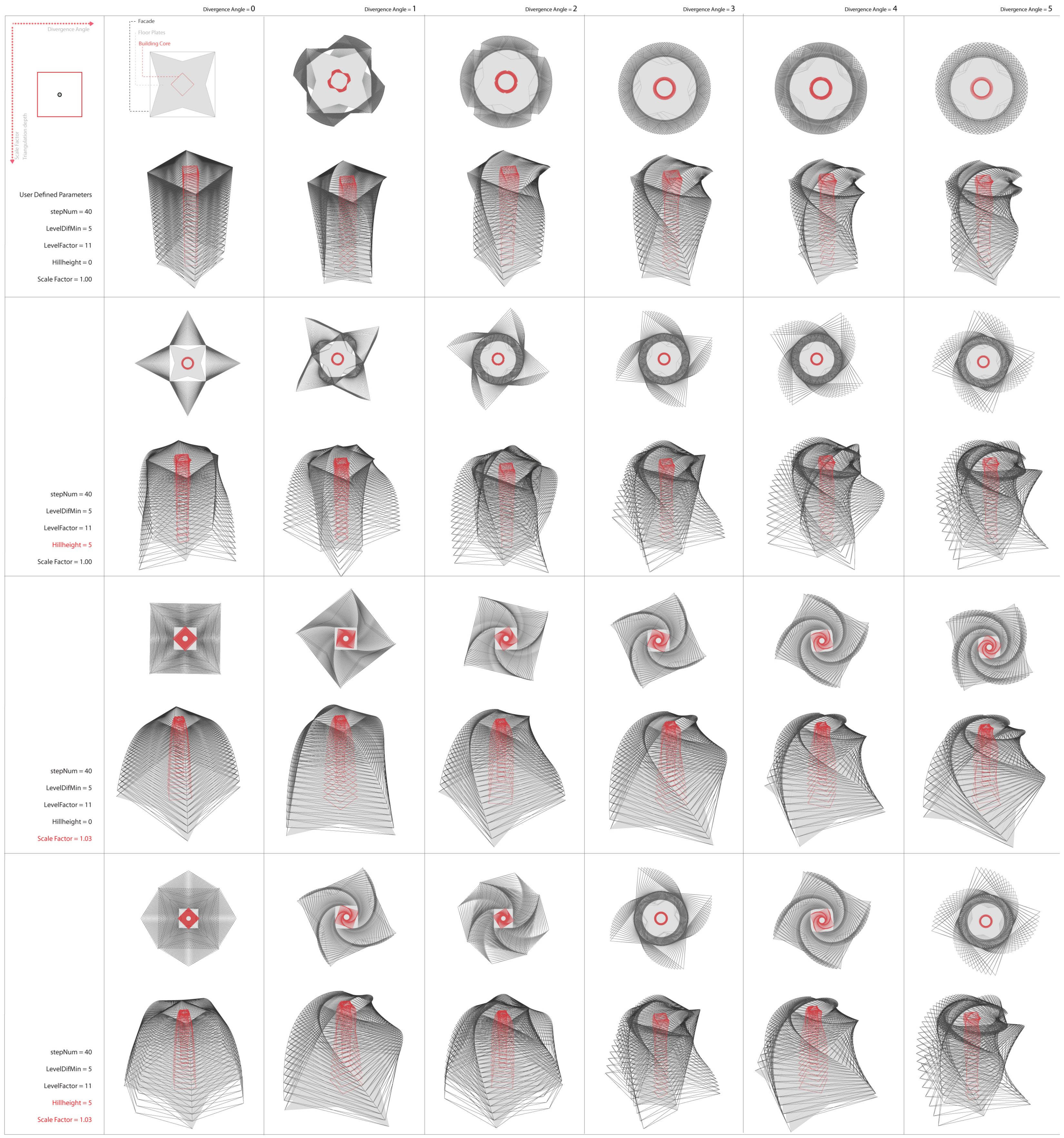


Figure 5.2 Three different architectural projections of the Cactus Script: (a) High-rise buildings, (b) built terrains, (c) double façades.

Table 5.4 A Set of Possible Architectural Inferences of the Script for High-rise Buildings.



5.4. The Process of Modeling and Transcoding: Nested Iterative Loops of Encoding and Decoding

Modeling is a cognitive activity,[203] since the modeler intends to establish abstract and consistent explanations for actual phenomena within representations. The modeler translates the information that she/he gathered from the real world to the language of the conceptual world. In other words, the modeler constructs a representative and explanatory system, which stands at the melting point of factual novelty and conceptual/theoretical construction. Through this process, there occurs continuous feedback and feed-forward loops between the researched object and the constructive theory. In the larger framework, the mathematical models of phyllotaxis, which have been mentioned and demonstrated in Chapter 4, can exemplify how a model develops through continuous feedback and feed-forward loops between distinct modeling studies conducted by a number of scientists and mathematicians. The phyllotaxis models will probably continue to evolve and develop as far as a modeler [re]looks, [re]examines, and [re]comprehends the natural phenomena. Hence, incessant observation, analysis, and modification are essential to advance the model towards a more precise, correct, consistent and comprehensive one.

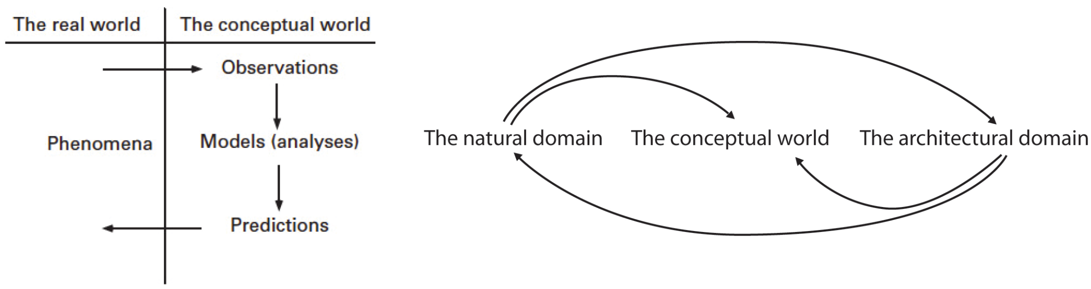


Figure 5.3 The information flow between the real world and the conceptual world through the processes of modeling: (a) Dym and Ivey's depiction for mathematical models,[204] (b) Author's depiction for transcoding computational models.

On the other hand, the 'transcoding' models act as mediatory devices between the natural and architectural organizations. The transcoding models do not only explain a natural phenomenon, but they also have to draw inferences for future architectural products and anticipate a design approach. Accordingly, the real world that the model delineates splits into two as the world of nature and the world of architecture, which the transcoding model needs

[203] Clive L. Dym. *Principles of Mathematical Modeling*. 2nd Edition. Elsevier Adacemic Press, 2004[First published in 1980]. p. 3.
[204] Clive L. Dym. *Principles of Mathematical Modeling*. 2nd Edition. Elsevier Adacemic Press, 2004[First published in 1980].

to negotiate on in the conceptual world.(Figure 5.3) Thus, the iterative loops of modeling turn out to be more complex, when there is an aim for transcoding: both the knowledge in the natural and architectural world needs to be unified and integrated with each other in a non-linear fashion. Besides, computational models of natural phenomena rewrite and re-express their objects with a level of abstraction and in a complete system. Within an inquiry on the application of these models in architecture, the computational model needs to embrace the comprehensiveness and flexibility that will appeal to generate a vast number of alternative outcomes that will express both the natural and the architectural organizations. Additionally, the iterative loops of observe, analyze, modify can be more rapidly carried out in transcoding natural processes to architectural design through computational models. The flexible, dynamic, and flexible character of a computational model enables the modeler reshape, modify, and improve the model more immediately and smoothly.

Since the architectural design is regarded as deriving from a possible outcome that is transcoded from nature's models, the computational model of the cactus needs to include the generative process that will give rise to an extensive range of possibilities. This can be obtained through building well-defined models, where dependencies and relationships are constant; and yet the interference of the user is expansive by means of user-defined parameters and initials. In this respect, the computational model, which is developed in the scope and aim of transcoding, shall evolve towards a more precise but at the same time more *ductile* model throughout its becoming process. In a ductile model, the architect may interfere to the model almost at any stage. The architect has control on the outcomes through the parameters and variables he/she defines; and yet the outcome is not a conclusion of an oppressive bias.

Learning and knowledge constitution continues throughout the transcoding practice in a multi-layered manner. Thus, it is crucial that the architect's role in modeling shall not stay limited with the architectural phase of knowledge transfer. Since the model and generative system is transparent and explicit; the architect is capable of interfering, modifying and making alterations whenever another order, relation or dependency is uncovered, established, and demanded. Thus, nested and layered iterative loops of observing-analyzing-generating-testing take place in the process of developing a model for transcoding.

Within each observe-analyze-generate-test cycle, the outcome of the model gives feedback to the modeler the fallacies, inadequacies, and promises for expressing the natural and the architectural. By evaluating these feedbacks, the modeler reconsiders the object of study, re/comprehends its generative systems, and reconstructs the model.(Figure 5.4)

Consequently, during constructing the model, the modeler conveys a process of continuous learning and knowledge constitution. Hence, the model observation and construction, analysis and synthesis are not sequentially ordered in a linear sequence but rather in an integrated multi-dimensional information flow between the object of study, the computational model, the modeler and the prospective architectural design. Manuel DeLanda evaluates the mentioned progress of computational constructs as 'virtual evolution', since a computational model includes rules, parameters, operations - the deriving laws of a morphogenetic process, which can be regarded as a 'virtual code/DNA.'[205] To sum, the virtual code of the cactus embraces the basic system for generating an extensive variety of cactus types; plus the parameters and variables defined in the system are the key promoters of such vicissitude.

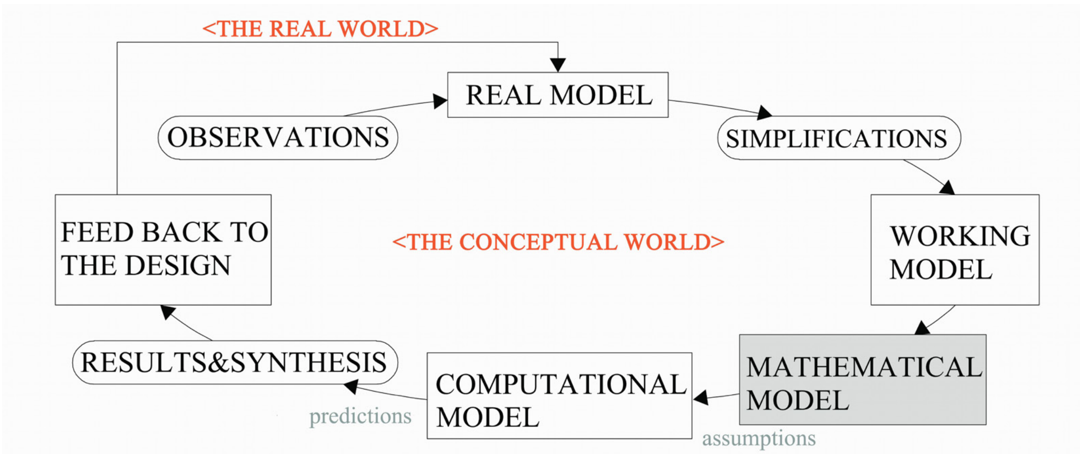


Figure 5.4 The cyclic process of modeling demonstrated by Arzu Gönenç Sorguç and Semra Aslan Selçuk. Evolution of the model (from more abstract towards a more complex, dynamic, comprehensive model).

Semra Aslan Selçuk, Arzu Gönenç Sorguç. "Exploring Complex Forms in Nature Through Mathematical Modeling: A Case on Turritella Terebra." *ECAADE 2009*, Istanbul, September 2009.

Except the feedback and feed-forward mechanisms between the object of study, theoretical framework, the computational medium, it must be mentioned the crucial external participation of the modeler in the becoming of the model. The modeler's insight about the probable future architectural indications is an undermined factor of modeling. By meaning indications, it is not implied the end-product of an architectural study but the generative system, which is the knowledge that the model transcodes from nature to architecture, being capable of generating architectural design processes. While constructing the model, the

[205] Manuel DeLanda. "Delueze and the Use of the Genetic Algorithm in Architecture." p.522.

architect simultaneously envisages/ considers/ evaluates the architectural implications of the generative process. That is why the modelers of such transcoding practice shall be architects, who may orientate the development of the model through the whole process from initial observations/analysis to the ultimate emerging architectural designs. Thus, in this manner the model goes through an evolution under the umbrella of architectural thinking.

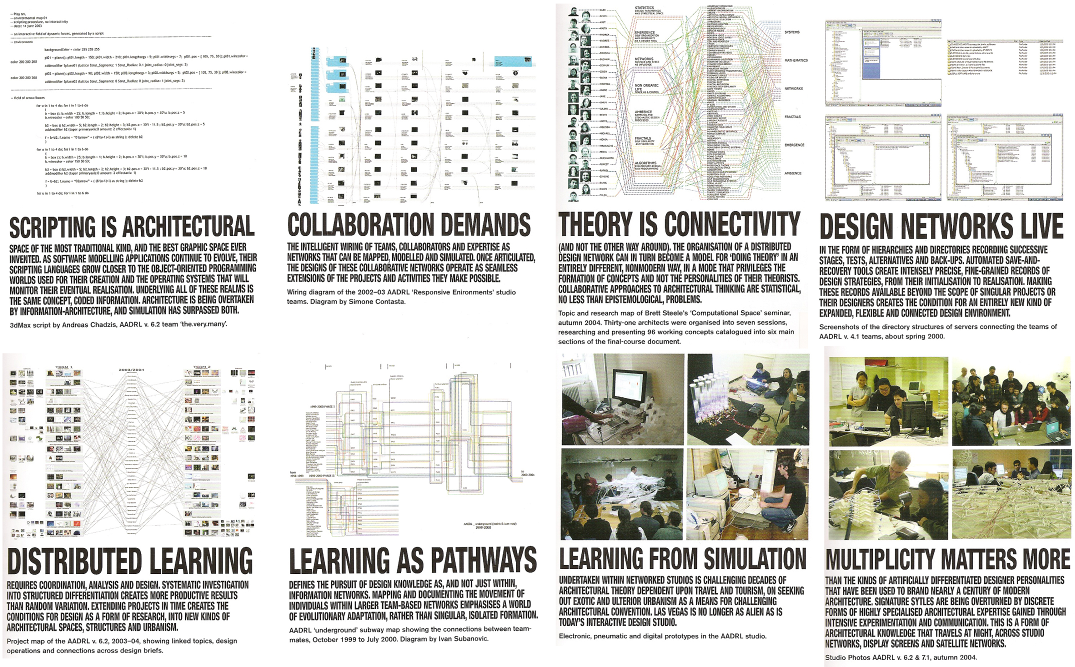


Figure 5.5 Slogans of the change in architectural design thinking within computational theory of AA Scool Design Research Lab.

Brett Steele. "The AADRL: Design, Collaboration and Convergence." *Collective Intelligence in Design: Architectural Design*. Vol 76, No 5, 2006.

Within a transcoding practice, the architect becomes the designer of a widespread information exchange environment, which turns out to be searching for a trans-disciplinary study. The computational model of cactus that is illustrated in this thesis shall be regarded as a pre-inquiry of a transdisciplinary study. For the model to be more complete and comprehensive to fulfill the requirements for an architectural product, knowledge from several other disciplines shall be integrated in the model. Architectural design includes inputs from various disciplines about structure and statics, mechanics, hydro-dynamics, acoustics in addition to social sciences. In this way, the transcode will establish transdsiciplinary knowledge constitution as well. Thus, while the architect as the modeler constructs a computational model aiming for transcoding natural processes, at the same time he/she should configure the plug-ins/nodes where information from various disciplines can be integrated in the model.

Within the aim of transcoding, the research object from nature, the simulation of the model, and the prospective architectural design are compositely investigated in the observation and analysis phases. In this thesis, while the modeler intends to construct a model within the common properties of several cactus species, she/he also intents to outline a generative mechanism such that exception, divergence, and difference can also be delineated. Thus, in order to make the computational model more comprehensive and descriptive, different cactus types are continuously re-examined. In this manner, the model produces more accurate explanations, whereas it also brings forward a larger set of possible outcomes.

5.5. Conclusions And Remarks About The Case Study

Computational theory presents thinking modes and mediums – thus models that enable [re]considering, [re]comprehending, [re]interpreting and [re]constructing our environment. Moreover, computational theory, thinking, and mediums are concurrently promoting and corroborating each other throughout establishing computational explanations of natural phenomena. As it is observed in the case study, the computational model of the cactus is shaped and structured by the interface's potentials, constraints, limits as well as its syntax and grammar. Thus, the computational medium has instructed/ restricted/ deliberated the generative process of cactus plants by introducing information flow patterns, dependency and relation editors, operations and rules, and a symbolic language.

The description of cactus in verbal, written or mathematical literacy would conclude to models that have distinct structures and distinct knowledge heritage. In a computational model, the inherited knowledge is process-based. The model constructed in this thesis expresses a dynamic and flexible generative process, which includes the associative intelligence of form, behavior, and growth belonging to cactus plants. Hence, the model constitutes the foundations of architectural form generation, while it enunciates similitude of behavior in architectural buildings and cactus body by means of the comprehensive and associative knowledge it inherits.

In a computational model, flexibility and perpetual novelty brings forth a populated of set of probable outcomes as results of the same generative system. Thus, constructing an integrated model of the cactus will generate a variety of outcomes that follow the same process, operations, rules, and still express similitude of behavior. In this manner, the computing and processing supremacy of computational mediums can be benefited from in the explorations for versatility and vicissitude in architectural solutions.

Moreover, the dynamic and integrated character of computational models is found to occur also in the modeling practice. The multiplicity of inputs/ interferences/ restrictions established by the modeler, the theoretical framework, and the research object, the medium and interface makes the model evolution progress towards a specific direction. In our case, the interface of Monkey Script Editor presents its own information processing syntax, symbolic language, and operations/tools. Thus the evolution of the model is established within the constraints, limits and potentials of Rhinoscript. For instance, another knowledge modeling interface such as Grasshopper would orientate the model towards another information processing structure, and thus lead to another generative system. In this respect, interface interacts dynamically with the research object, the modeler's constructive filter, and prospective architectural implications. Moreover, the script medium and interface defines the generative model – thus the cactus and the architectural product.

Besides, the modeler conducts a simultaneous and continuous learning process with the observe-analyze-generate-test cycles through the continuum of transcoding, modeling, designing. As the model is found insufficient, abstract or inadequate in being dynamic, flexible, and comprehensive, the modeler inserts new parameters, dependencies, and relations. In this manner, the modeler operates a mutual descriptive and normative practice while transcoding nature and architecture. Therefore, the evolution of the model corresponds with the evolution in thinking about the process, understanding the cactus and designing the architectural product.

Through transcoding, the universality of computation is the driving force of transferring knowledge from one domain to the other. In our case, computation acts as a 'mediatory link' for transcoding knowledge between the architectural and natural domains. Distinguishing from other mediatory links, computational model itself includes the transcoding algorithm as well as the explanatory and generative system. Thus, it becomes the interface of knowledge exchange, as opposed to being a tool for establishing knowledge exchange. Therefore, the translation of knowledge from nature to architecture occurs in one model, which refers to a duality of inferences. Consequently, the constructed model itself is the manifestation of transcoding, whereas the whole process of model construction structured/shaped within the eager to transcode.

CHAPTER 6

CONCLUSION

Computation, becoming an overarching theory and interface, presents both methods and mediums for [re]understanding, [re]interpreting and [re]building our environment. Through its models and structure of thinking, computation can describe natural and artificial phenomena with their underlying algorithmic patterns and make future projections about the alteration/variation of their generative systems through time. Thus, processes, relations, and dependencies turn out to be the major concerns of such a computational resolution of the world. Therefore, the concentration of architecture is shifting from designing an end product towards designing a generative model.

Architectural design requires multiple inputs from several disciplines. Nature provides us observable real cases to learn about the process of systems, natural and artificial. Moreover, computational theory, with its thinking modes and mediums, leads the practice of transferring the process-based knowledge of natural phenomena to architecture. Hence, through such an approach, computation turns to be an interface between nature and architecture, capable of transcoding knowledge from one domain to another.

In this thesis, the process of transcoding nature and architecture through computational models has been studied considering the becoming of the model, the becoming of the natural, the becoming of the architectural – i.e. the becoming of the architectural knowledge that focuses on algorithmic generative processes. Thus, throughout the thesis, process is appraised as the key for understanding organizations at different levels and domains of reality. Computational theory enables clarifying the order and structure of complex systems. Hence, through computational thinking and mediums, architects re/assess system processes by their relations, dependencies, potentials, limitations, probable generations, and possible evolutions.

6.1. Contributions of This Research

In this study, the case of cactus has been acknowledged as a source for learning about the association of form and performance as an integrated mechanism, which provides solutions in challenging climates, and thus proposes informative, constructive and favorable solutions for architectural products. Through this inquiry, a 'method' for transcoding nature to architecture has been explicated, while at the same time a 'tool' for transcoding cactus intelligence to architectural buildings, terrains, and façades has been developed.

Therefore, one of the contributions of this thesis to the field of architecture is the proposed method of design, which schedules analytical and computation-based reconsideration, recomprehension, reinterpretation, and reconstruction of natural processes through models such that their form generation processes can lead and surmise to architectural products. Through this method, the conceptual framework of 'transcoding' portrays the bilateral aspect of computational modeling as it refers and infers to both natural and architectural organizations. The thesis inquiry subjects the performance-form association of cactus plants in favor of their adaptability and survival in challenging environments. Thus, the procedure illustrated in this thesis can also be recognized as a method for environmental friendly architectural design.

Secondly, Cactus Script can be listed as one of the contributions of this thesis. The Cactus Script can be used as a tool for form finding that emerges from performative competence for sun-shading, water-collecting, and air flow control. Thus, this tool can be utilized in the form finding explorations for high-rise buildings that needs to resist and orientate external wind forces, while it needs to circulate fresh air in the internal volume of the building. Moreover, the sun-shading performance of the building will improve the inner spatial conditions of the building, whereas the water collecting performance will present the building a self-sufficient and sustainable character. Other than high-rise buildings, this tool can also guide the form finding explorations for built terrains, or double skin façades that can be applied on straight or curved surfaces as it was explained in Chapter 5. To sum up, the tool of Cactus Script can provide draft plans for architecture that paves the way for developing passive systems for built environment. In this manner, the tool and method proposed in this thesis offer solutions to the contemporary dilemmas of architectural design, since it can be utilized to eliminate the formal shortcomings of architectural products.

The results of the thesis inquiry do also contribute to the discipline of architecture with general deductions about the ‘performance of form’, since vast number of outcomes of the Cactus Script nourishes observation, evaluation, and comparison of specific forms and their performative capacity. It can be observed that channels built on the external surface of form enable water collection and water storage of a building, whereas recessions grant the self-shading and self-conditioning performance. On the other hand, the egg-shaped or double-curved surfaces in addition to the spiralization of channels inherit the building a better reaction towards external wind-forces. When the recessions are additionally defined with slight openings, the building do also possess the potential to absorb the controlled wind inside the building, and establish air circulation and self-conditioning in the inner volume.

Furthermore, an integrated, algorithmic and three-dimensional perception of phyllotaxis has been introduced in this thesis. The developed parametric model of phyllotaxis can be counted as one of the contributions of this research. The phyllotaxis models, which have been investigated and developed as mathematical systems for over a hundred years, haven’t conjured up a major insight in the architectural studies. It can be claimed that the absence of phyllotaxis models in architectural studies is reasoning from the complicatedness of the mathematical equations, and the recognition of the architect himself as a descendent consumer rather than a contributor in the modeling process. In such an approach, the architect has no adequate knowledge about the model to modify and develop it, or to draw relations between the modeled system and architectural design.

Another contribution of this thesis to architectural literature can be listed as the reinterpretation of Frederick Jameson’s term ‘transcoding’ as a method for inquiry on the conjunction of nature and architecture, and as the indispensible maneuver of computational design processes. Besides, this thesis recognizes ‘model’ as the essential mediatory device and interface, which establishes the transcoding of natural knowledge to architecture and determines the limits, potentials, prosperity, and modifiability of the transferred knowledge.

Constructing computational models of cactus that explicate the systematic structure of information flow/generative process, is essential for transcoding the intelligence/knowledge of cactus system behavior to architecture. Thus, ‘transcoding through computational models’ departs from the previous analogical approaches of making direct mimicries or translations of natural form. It can be observed that the established level of complexity, association, and flexibility in the transcoding model is majorly dependant on the modeling literacy, mode of representation, and constructive theory of computation. The parametric and multi-dimensional assets of the model, the rapid processing time of its generations, evaluations, and analysis have been the advantageous proceedings of computational systems. Additionally, these qualifications of the model also support and accelerate the explorations and experimentations for possible architectural inferences.

6.2. Recommendations for Future Work

The cactus model structure draws an agenda of transdisciplinarity, since the proposed generative process determines the dependencies between different modes of knowledge that belongs to distinct disciplinary boundaries. In this respect, architecture, computational design and scripting, biology and fluid dynamics have been the major knowledge areas that have supplied the development of the Cactus Script. Yet, the author's limited knowledge in the area of fluid dynamics has prevented the integration of the computational fluid dynamics analysis and evaluation to the Cactus Script. This aspect of the model can be taken as a starting point for further work, which can focus on the integration of fluid-dynamics evaluation procedure in the form finding process. If the CFD analysis is integrated in the model, the performative evaluations can be established simultaneously, and thus it will be possible to qualify some forms superior in terms of their performative capability. In this manner, the set of possible outcomes can be reviewed through the processing of the model, and a couple of preferred forms can be elected mechanically for their competence to the environmental conditions. Certainly, such a model should be subject to a more transdisciplinary research and can be constructed by an interdisciplinary team.

It shall be emphasized once more that in this thesis the Cactus Script has been acknowledged as 'one of the many' possible transcoding models that can be developed. Thus, it can be examined in the future studies if cactus intelligence can flourish another associated computational model that will provide new implications and inferences for architectural design.

In this study, cactus studies have been focused in order to explicate and illustrate a transcoding process between nature and architecture, which is assessed to be advanced in virtue of computational media, tools, and mode of thinking. However, it is possible to draw process-based knowledge exchange between any natural organization and architecture through computation models. Moreover, it is also possible to re-analyze, re-comprehend, rewrite artificial organizations, and extract relevant knowledge and information that can enhance and conjure up prospective expansions in architectural design. Further architectural inquiry can establish upon the application of the illustrated method for transcoding the intelligence of any other natural or artificial organization to architectural products.

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APPENDIX A

PSEUODOCODE OF THE TRANSCODING CACTUS SCRIPT

(The explanations are given in italics.)

1. TAKE USER'S DEFINITIONS FOR THE PARAMETERS:

coreGeo, stepNum, Ang, LevelDifMin, LevelFactor, Hillheight

2. BUILDING AND CONTROLLING THE GLOBAL OUTLINE OF THE FORM THROUGH POLYGONAL GROWTH:

-Populate the Core Geometry by scale, rotate, copy and move commands.

For x = 0 To **stepNum**

If x = 0 Then

CoreF(x) = **CoreGeo**

Move(x) = **-** (**LevelDifMin** / 100)

-Populate the first half: top domed form of the cactus.

If x< (stepNum/2)

Move(x) = (Move(x-1) *(**LevelFactor**/10)

CoreF(x) = Scale (CoreF(x-1) , Center(0,0,0), ScaleFactor(1.1, 1.1, 1.1), copy)

Rotate (CoreF(x), Center(0,0,0), **Ang**(0-180))

Move(CoreF(x), FirstPt(0,0,0), ScndPt(0,0, - Move(x))

-Populate the other half: parabolic form of the cactus.

If x > ((StepNum/2)-1)

Move(x) = (Move(x-1) *(**LevelFactor**/10)

CoreF(x) = Scale (CoreF(x-1) , Center(0,0,0), ScaleFactor(1.1, 1.1, 1.1), copy)

Rotate (CoreF(x), Center(0,0,0), **Ang**(0-180))

Move(CoreF(x), FirstPt(0,0,0), ScndPt(0,0, Move(x))

3. DRAW THE PHYLLOTACTIC SPIRALS BY INDICATING THE VERTICES OF THE POLYGONS AS CONTROL POINTS:

-Extract and Group the Vertices of each polygon at each level.

For x = 0 To **stepNum**

VerticeF(x) = Polyline Vertices (CoreF(x))

-Call the Vertice Points of the polygons in sequence and order, to draw the spiral

For y = 0 To **stepNum**-2

VerticePts1 = VerticeF(y)

VerticePts2 = VerticeF(y+1)

For z = 0 To "Number of Edges of the **CoreGeo**"

spiralF = draw a line (from VerticePts1, to VerticePts2)

Put the line to "spiralF" layer

-Join the seperately drawn line segments together.

LineSegments = Call all the objects in "spiralF" layer

Spiral = Join (LineSegments)

4. ADD SURFACES AND AREOLE HILLS OF THE CACTUS:

-Define the corner points of each surface segments for each polygon

For t = 0 To StepNum-3

- Regroup vertices of each polygon layer as Vrtcs1, Vrtcs2, Vrtcs3

Vrtcs1 = VerticeF(t)

Vrtcs2 = VerticeF(t+1)

Vrtcs3 = VerticeF(t+2)

-Define two types of tesselations: one for vertical ribs , and one for spirals

For u = 0 To "Number of vertices of the Core Polygon"

-Find the peak point for triangulation and areole hills:

-Calculate Midpoints

Line1 = Draw a Line (from Vrtcs1(u), to Vrtcs2(u+1))

MidPoint = Divide Line (Line1, 2 Segments)

-Calculate Surface Normals

Srf1 = Draw a CornerPt Surface (Vrtcs1 (u), Vrtcs1(u+1), Vrtcs2(u)))

Normal = Define the surface normal vector (Srf1)

-Calculate Areole Normals with user specified height

AreoleNormal = Multiply vector (Normal, (t* (**Hillheight**/10)))

-Add the peak point of the areole hills

AreolePt = Move point with a vector (MidPoint, AreoleNormal)

-Draw triangulated tesselations from each polygonal vertice to the AreolePt.

Tri1 = Rhino.AddSrfPt (array(Vrtcs1(u), Vrtcs2(u), AreolePt))

Tri2 = Rhino.AddSrfPt (array(Vrtcs2(u+1), Vrtcs1(u), AreolePt))

Tri3 = Rhino.AddSrfPt (array(Vrtcs2(u), Vrtcs3(u+1), AreolePt))

Tri4 = Rhino.AddSrfPt (array(Vrtcs3(u+1), Vrtcs2(u+1), AreolePt))