Manipulating L-systems:

Controlling the behaviour of L-systems in architecture methodologically

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Abstract

An L-system or Lindenmayer system is an algorithm for modelling the growth of many organisms found in nature such as plants, human brain, circulatory systems, etc. Due to the hierarchic structure of the algorithm it is often misinterpreted to have a limited capacity of morphological differentiation. However, setting simple rules for the algorithm can make the system strategically manipulable.

This essay will challenge to put together the methods for controlling the behaviour of L-systems and prove that these algorithms are highly capable of adapting into various context.

The investigation of 'methods' includes the examination of natural processes and also prior research on computational simulation of L-systems as well as the prior applications of L-systems in the practice of architecture. The work of Przemyslaw Prusinkiewicz, John Frazer, Michael Hansmayer, Michael Weinstock, Michael Hensel and Achim Menges will be analysed as reference.

As a result, a set of rules for making an L-system indirectly controllable will be classified and combinations of these rules will be offered in order to integrate these algorithms into the field of architecture.

Contents

Introduction

Imagine one circulatory system in a body that is capable of transmitting matter from any source to any destination and at the same time having the smallest volume as possible.[1] How would it look like? How would a growing organism be structured in order to allow continuity of growth while consistently maintaining the system in a bottom-up hierarchy? These simple design problems are solved in nature by using the L-systems.[2] The term *L-system* is introduced by the biologist Aristid Lindenmayer in 1968.[3] An L-system or Lindenmayer system is an algorithmic abstraction for modelling the growth of fractal organisms found in nature such as plants, human brain, circulatory systems, etc.[4]

Using fractals and self-similarity in architecture is common since ancient times. The cathedral of Anagni (Italy) that is built in 1104 is ornamented with mosaics in the form of fractals.[5] More recent developments in digital computation and fabrication technologies allow integration of biological paradigms into architecture as generative processes with less labour and thus opens up new possibilities of spatial articulation and new fabrication methods.

In contrast to the diversity in nature, products of L-systems are often misinterpreted to have a limited capacity of morphological differentiation due to the linear and hierarchic structure of the algorithm. However, setting strategic rules for the growth process can make the system highly manipulable. Interpretation of L-systems as a geometrical form in architectural practice can be influenced by but not only limited to the natural systems.

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[1] G. William Flake, The Computational Beauty of Nature (New York: The MIT Press, 1998) 77.
[2] Flake 77.
[3] P. Prusinkiewicz, The Algorithmic Beauty of Plants (New York: Springer-Verlag, 1990) 2.
[4] Flake 78.
[5] Sala, N. Fractal Models in Architecture: A Case Study 16 Dec. 2010 <http://math.unipa.it/~grim/Jsalaworkshop.PDF>.

Manipulation of L-systems in theory

Growth functions are the lowest level rules of directing the behavior of an L-system. Having simple rules of production makes the entire process of growth controllable in a bottom-up manner. Every individual cell in the system contains the same instructions of growth, like a DNA, while they differentiate from each other by processing the same information according to their own specific conditions in the system. The most basic and simple syntax of a growth function consists of one *axiom* that represents the seed cell and a *rewriting scheme* that is responsible for taking the *axiom* and substituting the symbols as specified by the rules.[6] After the substitution, the new string becomes the *axiom* for the next iteration.[7] The string values are then converted into geometrical data in order to visualize the algorithmic process. As a result, the length of the resultant string increases exponentially in each iteration, and so the number of branches in the system.

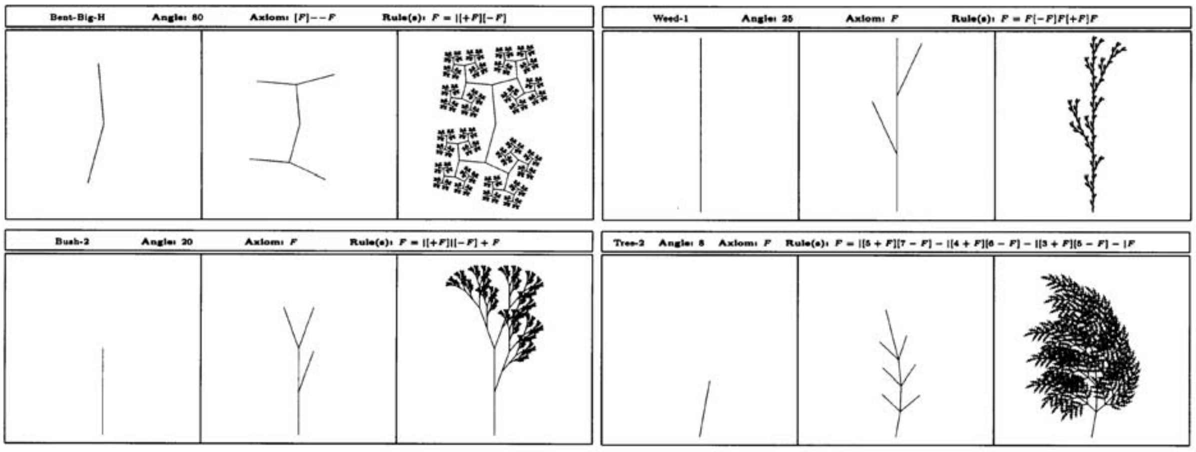

Figure 1. *Simple branching fractals*.[8]

Taking the algorithm from an abstract level to a more materialised state, Yukio Minobe tests Murray's law in his research about branching patterns, in order to optimize the attributes of the outcomes. Murray's law is a formula that calculates the radii of new branches in accordance with the previous branches. [9] The aim of the formula is to find the optimum radius in a circulatory or respiratory system.[10] Growth of the L-systems can be adjusted by applying similar rules of optimisation.

Combining many of such *growth functions* to produce a system, in other words, merging the patterns of growth, provides complexity. Christopher Hight explains this emergent behaviour as a result of *moiré effect*, where "local variations of the components work at an entirely different scale from the global pattern which emerges".[11] Modifying the initial rules of growth results in unexpected behaviour of the system at the global scale. Dramatic effect of nesting additive waves can be observed in the following graphs.

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[6] Flake 78-79.
[7] Flake 79.
[8] Flake 84-87
[9] M. Weinstock, et al., Emergent Technologies and Design (Routledge, 2010) 161.
[10] Weinstock, Emergent Technologies and Design 161.
[11] C. Hight, "Epistemologies of Measure, Order and Differentiation in Modern Architecture," Morpho-Ecologies, ed. M. Hensel and A. Menges, (London: Architectural Association, 2006) 355.

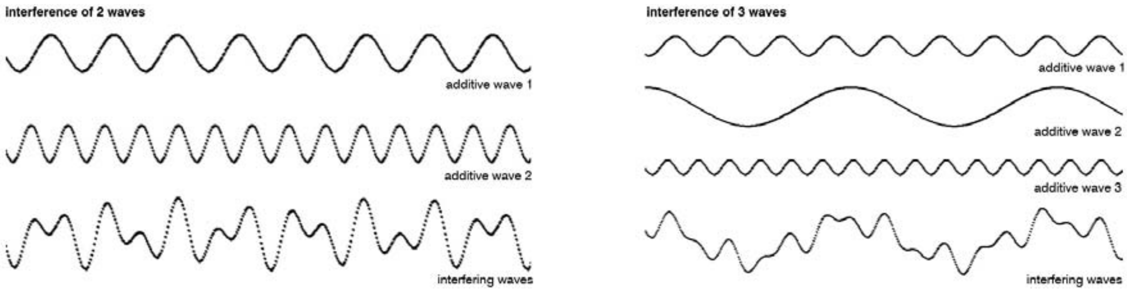

Figure 2. *Wave interference*[12]

In a system that has completely deterministic rules, growth is predictable and repetitive. However, *stochastic L-systems* creates a variation within the same species by randomizing the rules. Different probabilities of production allows a variation of geometry in the systems that are produced with similar rules while the underlying topology remains unchanged.[13] *Lakehouse Patagonia* project by Bollinger and Grohmann is a typical example of stochastic L-systems where variation in the structure is achieved by randomly modifying the parameters of branching angle and branch length.[14]

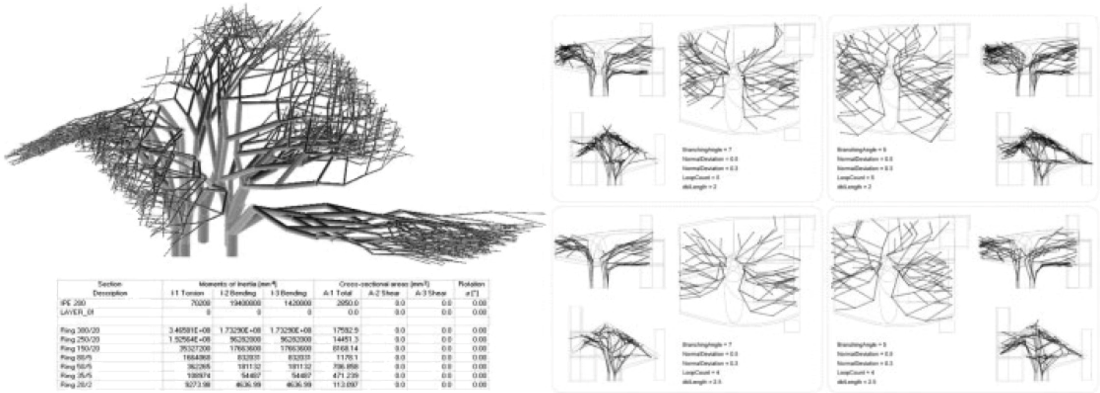

Figure 3. *Archiglobe, Lakehouse Patagonia, Argentina, 2007*[15]

Basically, productions of L-systems are applicable regardless of the context in which they appear. However, production application may also be dependent on the predecessor's context.[16] This dependency of products to the seeds establishes a communication between different levels of the hierarchy in an L-system by providing an information flow from roots to the branches. *Context-sensitive L-systems* give the opportunity of modifying the production rules according to the evaluation of the predecessor's situation. In the same project Bollinger and Grohmann optimise the structure by evaluating the previous iterations. "The evaluation of each iteration includes both architectural as well as structural aspects, considering not only topological relations but also related dimensioning of elements."[17]

Due to the rule based production methods of L-systems, *parametrization* accelerates the process of design research dramatically. Similar rules with different parameters may be responsible for the formation of various resultant geometries. Patrick Schumacher describes *parametric responsiveness* as the inbuilt kinetic capacity that allows articulation of the environment to reconfigure and adapt itself in response to the prevalent patterns of use and occupation.[18] Searching through basic parameters of an L-system provides results with different performative capabilities and allows an analytical process of optimisation. Following images illustrate the optimal ratios of branch lengths that produce the most

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[12] Images are produced by the author in Processing.
[13] Prusinkiewicz 28.
[14] "Form, Force, Performance: Multi-Parametric Structural Design," AD Versatility and Vicissitude (Wiley: March/April 2008) 23.
[15] "Form, Force, Performance: Multi-Parametric Structural Design," 24.
[16] Prusinkiewicz 30.
[17] "Form, Force, Performance: Multi-Parametric Structural Design," 24.
[18] P. Schumacher, "Parametricism as Style – Parametricist Manifesto" 2008, 14 Dec. 2010 <http://www.patrikschumacher.com/Texts/Parametricism%20as%20Style.htm>.

equitable distribution of leaf clusters. Interestingly, computed optimal results are very similar to the observed ratios in real trees.[19]

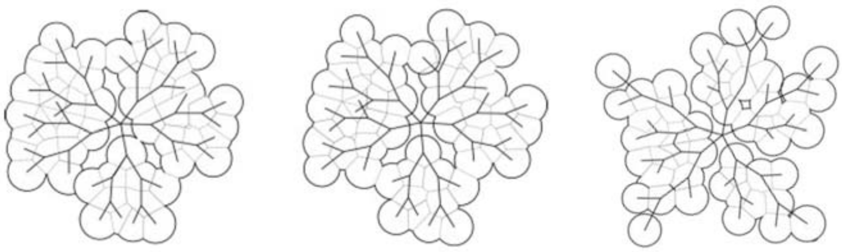

Figure 4. *Leaf clusters*[20]

Although L-systems initially have specific rules of growth, they can differentiate their behaviour segmentally according to external controls such as attractors or repulsors. Yukio Minobe deploys *centroid branching algorithms* to control the direction of growth. Predefined end points attract the new branches that grow out of the seeds.[21]

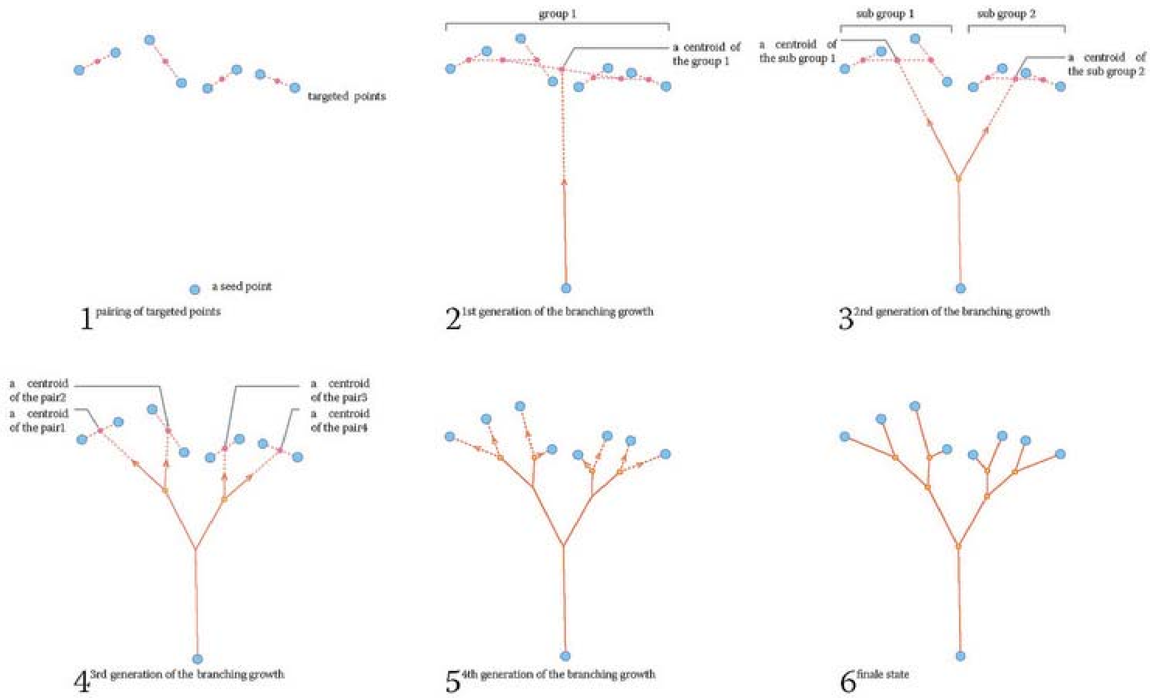

Figure 5. *Centroid branching algorithm*[22]

Manipulating the system with external stimuli provides a different level of control than the bottom-up growth functions.

Another mechanism of controlling the growth are *mutations* which are the minor changes in DNA that result in unexpected behaviour of an organism.[23] In architectural terms, mutations and mutant behaviour stand for exceptional characteristics of a system, where these exceptions can either be responsible for enabling the transition of design between different states or leading to a new singularity. Mutating the *growth functions* creates new sequences of different characteristics in an L-system and consequently the growth becomes unpredictable.

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[19] M. Weinstock, "Metabolism and Morpholgy," AD Versatility and Vicissitude (Wiley: March/April 2008) 27.
[20] Ibid.
[21] Weinstock, Emergent Technologies and Design 158.
[22] Y. Minobe, Centroid Branching Algorithm Online Image, 2009, 14 Dec. 2010, <http://www.flickr.com/photos/architecturalecologies/4185027710>.
[23] A. Griffiths, "Mutation (Genetics)," Britanicca Online Encyclopedia 14 Dec. 2010 < http://www.britannica.com/EBchecked/topic/399695/mutation>.

Differentiation of L-systems in nature

Differentiation of species generate the plenty of diversity in nature. A pine tree is different from a broccoli not only morphologically but also topologically although they are both derivations of L-systems. Even with the same growth functions and the same number of iterations and components, various morphologies can be obtained from an L-system by changing the parameters of geometrical relations between parts. Branch angles and the ratios of length are the intrinsic characteristics of a particular species of a tree. In elm trees, each leaf springs from a stem at the same angle and they are rotated 180 degrees sequentially so that they are offset from each other. Instead of 180, rotating the leaves 120 degrees creates the structure of a beech tree, 144 degrees an oak, 135 degrees a poplar tree and rotating the leaves 130.46 degrees produces the morphology of an almond tree. [24] Parametrics in nature define the boundaries of species.

Darwin explains *evolution* as the change of organisms through successive generations and defines *natural selection* as the "principle by which each slight variation, if useful, is preserved."[25] Iterative structure of L-systems allows the refinement of their properties through the generation process. The system evolves consistently in each iteration by filtering the defects and saving its strengths. John Frazer proposes using defects as information systems whereby "the model is adapted iteratively in the computer in response to feedback from the evaluation."[26] Evolution provides a self-improvement mechanism in nature by reinforcing the systems with successive developments. However, the strength of it is limited by small improvements for the optimization of a system which already has a satisfactory solution.[27] In cases where more radical improvements needed, more sophisticated techniques have to be applied.[28]

Aside from genetic differentiation, plants are highly sensible, sensitive, responsive and thus highly adaptable to various external conditions such as light (phototropism), gravity (gravitropism) and newtonian forces (thigmotropism).

Figure 6. *Phototropism*[29]

Figure 7. *Gravitropism*[30]

Figure 8. *Thigmotropism*[31]

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[24] Weinstock, Metabolism and Morphology 29.
[25] C. Darwin, Origin of Species 1859, 14 Dec. 2010 <http://embryology.med.unsw.edu.au/pdf/Origin_of_Species.pdf> 33.
[26] J. Frazer An Evolutionary Architecture (London: Architectural Association, 1995)
[27] Ibid.
[28] Ibid.
[29] Phototropism Online Image, 14 Dec 2010, < http://www.f1000scientist.com/2007/5/1/69/1/>

Michael Hensel states that “It is possible to evolve plants digitally that are ‘grown’ according to environmental input. Every change in the input yields a different growth result. In other words, a different articulation of the modelled species.” [32] He also comments on Przemyslaw Prusinkiewicz’s research in the field of computational modelling of plant growth and development that “the gravity input can inform structural behaviour that is then negotiated with exposure to environmental input, for example to collect sun energy, rainwater and so on.”[33] This concept of real-time interaction between the design product and its environment abolishes the challenge of step-by-step, objective-by-objective optimisation of the system at the end of the design process, that is undertaken by specialists who are not involved in the design phase.[34] Rather than traditional methods of optimising and reconfiguring the system as a post-process of design, responsive organisms of nature exemplifies a new paradigm for architecture that involves self-optimisation in the generative process through response to external stimuli.

One such example of differentiation of plants according to various external conditions is the climatic adaptation. In environments with high levels of light, density of the leaves is higher relative to darker environments, while the lowest leaf can still capture sufficient light for photosynthesis.[35] Other species that are adapted to lower light environments “reduce their self-shading by producing flatter, shallow mono layered crowns with a single layer of leaves on the boundary of the leaf volume.”[36] Context-sensitive aspect of differentiation in plants is relevant to architecture in terms of site-specificity. Versatility can be achieved by generic rules. Emergence!

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[30] Kleuske, Gravitropism Online Image, 14 Dec 2010, < http://upload.wikimedia.org/wikipedia/commons/b/ba/Upsidedown-tree.JPG>.
[31] C. Meloche, Thigmotropism Online Image, 14 Dec. 2010, < http://www.ars.usda.gov/is/graphics/photos/sep05/d199-1.htm>.
[32] M. Hensel, “Computing Self-Organisation: Environmentally Sensitive Growth Modelling” AD Techniques and Technologies in Morphogenetic Design (Wiley: March/April 2006) 13.
[33] Hensel 14.
[34] Ibid.
[35] Weinstock, Metabolism and Morphology 29.
[36] Ibid.

Application in architectural practice

Recent developments in computational sciences and technology have resulted in significant advances in architecture and in the fields of modelling and visualisation. In more specific terms, Michael Hansmeyer states that "the integration of scripting languages into CAD applications enables the direct visualisation of objects using algorithmic processes."[37] The techniques of implementing L-systems into architecture will be analysed through four experimental projects.

Case 1:

In his *L-systems project* Hansmeyer is examining whether the latest developments in computer sciences open up new possibilities for architecture and exploring the methods of interpreting nature's algorithmic growing processes in the field of architecture.[38] The first method Hansmeyer offers is mapping the resultant strings of L-systems directly to architectural information such as surfaces, individual objects and derivative forms. On his first experiment, Hansmeyer maps the string values of an L-system to y-coordinates of the vertices of a grid surface. In his further experiments, he also creates a population of differentiated components by controlling the attributes of individual objects, such as scale and rotation.[39]

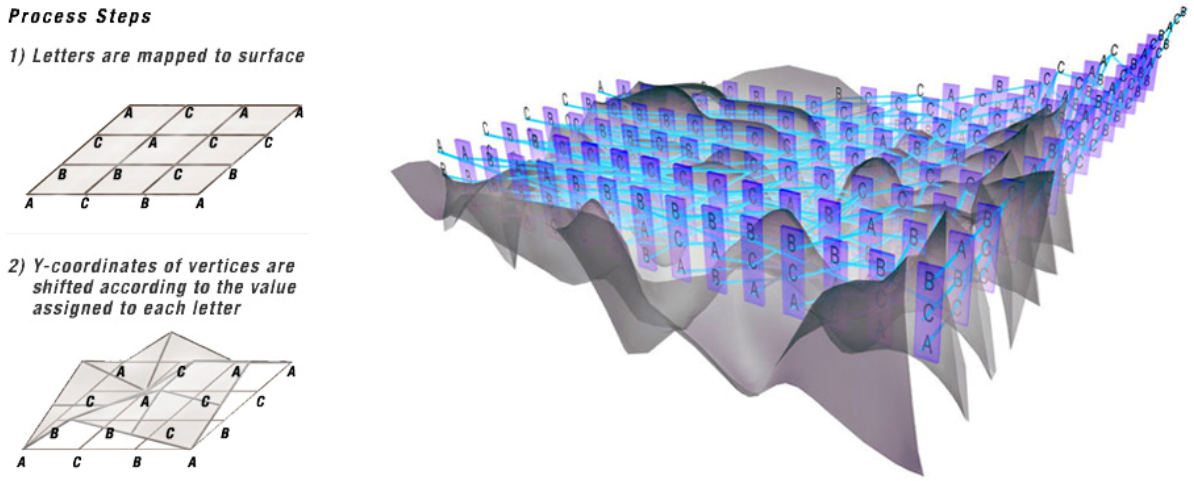

Figure 9. *Mapping L-systems to surfaces*[40]

As a second way of transferring data from pure algorithmic output of L-systems to architectural practice, Hansmeyer experiments on execution of turtle graphics in formation of geometries. He drives paths that change their attributes of movement, rotation, radius, branching and surface properties by using stochastic and deterministic L-systems.[41] The method of using turtle graphics instead of mapping the algorithm to existing objects is potentially responsible for more emergent behaviour, since it starts building geometries from scratch and depends on self-organisation.

[37] M. Hansmeyer, L-Systems in Architecture 2003, 14 Dec. 2010 <http://www.michael-hansmeyer.com/projects/project3w.html>.
[38] Ibid.
[39] Ibid.
[40] Hansmeyer.
[41] Hansmeyer.

Case 2:

In *Digital growth and ontogenetic drifts*, Achim Menges maps the digitally simulated growth to the propagation of architectural components in a similar manner as Hansmeyer. "The surface geometry generated through a digital growth process based on extended Lindenmayer systems provides the geometric data for an algorithmic distribution of parametric components, which results in a complex network of self-interlocking straight members that are immediately ready for production."[42] Having complex internal and external interactions and a non-linear interpretation of L-systems creates a non-deterministic outcome of the growth process.[43]

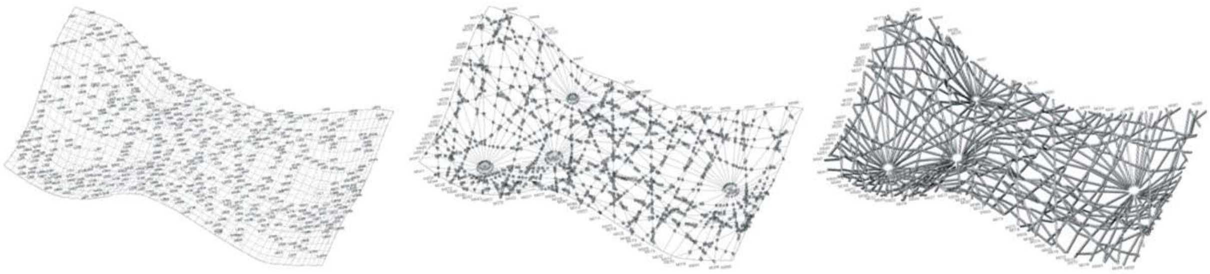

Figure 10. *Digital growth and ontogenetic drifts*[44]

Case 3:

Pavel Hladik's research on applications of L-systems in architecture focuses on physical and digital form-generation and form-finding processes that are dependent on structural and spatial performance criteria and also constrained by the material and manufacturing limitations.[45] Particularly this project includes multiple methods of interpretation in one system.[46] Hybridization of different processes provides heterogeneity and functional specialisation of parts in the system. Following images illustrate the differentiation of branching algorithms with a transition from vector-active to a surface-active system driven by stress analysis in ANSYS.[47]

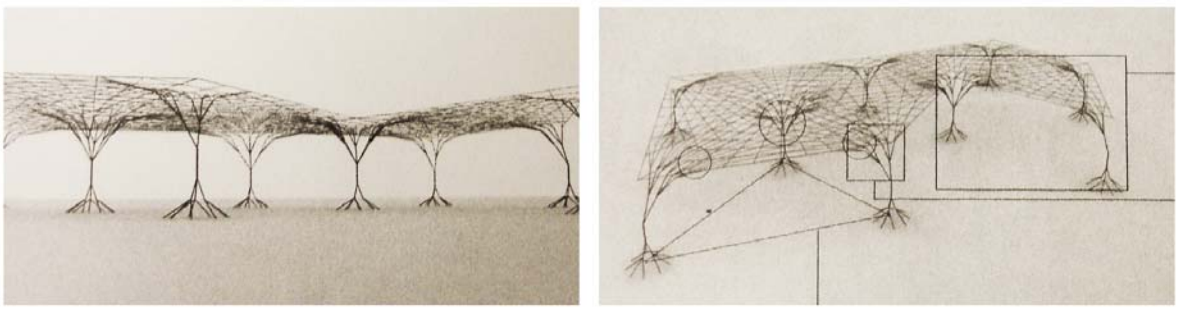

Figure 11. *Branching system with a transition from vector-active to a surface-active system*[48]

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[42] M. Hensel, "Polymorphism" AD Techniques and Technologies in Morphogenetic Design (Wiley: March/April 2006) 86.
[43] Ibid.
[44] Ibid.
[45] Weinstock, Emergent Technologies and Design 161.
[46] Ibid.
[47] Ibid.
[48] Ibid.

Case 4:

In *New Czech National Library*, OCEAN and Scheffler + Partner use branching algorithms as a generative tool to design a heterogeneous space that changes its articulation in a gradient to meet the programmatic and functional needs and that is at the same time structurally optimized in response to evaluation of the system driven by structural and spatial analysis.[49] The building consists of a solid and opaque volume in the centre that is occupied by the national archive which is the core of the library and two more volumes that are cantilevering from both sides of this massive structure. Structural articulation of the cantilevering volumes differentiates gradually, starting from five root points that carry the cantilevering mass to the end of thinner branches that allow more light to be taken inside the envelope. Michael Hensel and Achim Menges comments on this project that "Inherent variations of structural input data and parameters lead to the generation of a differentiated, tectonic envelope in which the interrelation of form, load-bearing behaviour and organisational capacity is synthesised."[50] Interference of multiple branching algorithms demolishes the linear hierarchy of L-systems and provides a range of heterogeneous differentiation.

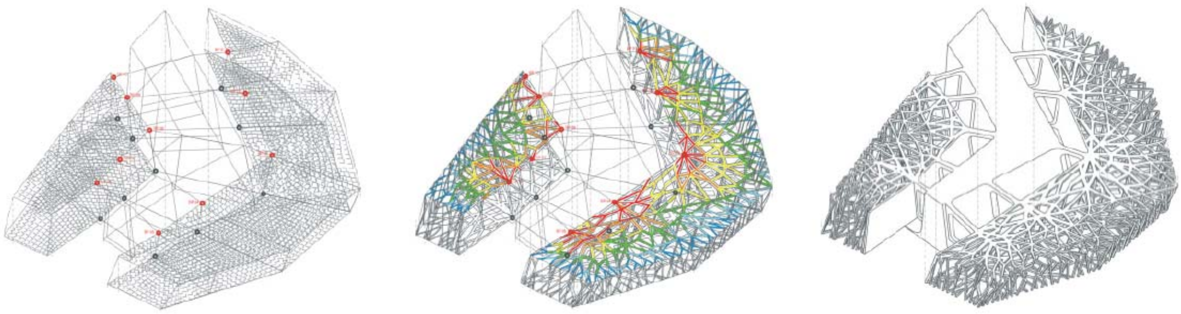

Figure 12. *OCEAN and Scheffler + Partner, New Czech National Library, Prague, 2006*[51]

[49] M. Hensel and A. Menges, "Designing Morpho-Ecologies: Versatility and Vicissitude of Heterogeneous Space" AD Versatility and Vicissitude (Wiley: March/April 2008) 107.
[50] Ibid.
[51] Hensel and Menges 105.

Conclusion

As a result of this paper, theoretical and practical methods of manipulating L-systems, with regard to observation of natural processes and re-examination of prior research, can be classified into three groups as the internal bottom-up growth functions of the algorithm, inter-systemic relationships between multiple systems and external control mechanisms which enable a more direct way of dictating the design in a top-down manner. Combining these methods as different layers of control at different levels provides complex outcomes that are to a high degree differentiable and optimised in many aspects of performance criteria.

Implementation of L-systems, that are controlled by such procedures, in architecture as a generic design tool enables architects to specify the characteristics of formation and materialisation through the process of design in a remarkably manipulative way and has the capacity of being adapted in response to the specific requirements of design context. L-systems are highly manipulable and adaptable to various conditions.

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