Architectural Narratives

Framework for Geometry Adaptation through Representations of Voxels and Tetra-Meshes

By

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Abstract

The growing influence of computing and digital technologies is creating a landscape of rapid change in both societal and urban structures. It is critical to explore a framework for architectural production that adapts and constantly negotiates with its context, conceiving of built forms as entities capable of resilient and adaptive behavior.

This research explores possible mediating languages that are capable of embodying traces of generative behavior resulting in geometries that are adaptable to context and design decisions. More precisely, it explores voxels and Tetra Meshes as computational representations affording morphological and adaptive behavior in architecture.

This thesis explores the question: *Can a simulation environment bring to light the specific geometric affordances of voxels and Tetra Meshes in a way that enables morphological changes that suggest this adaptiveness?*

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Introduction

In an age of sustainability, architecture is coupled with availability of new technologies that allows evaluation and adaptability in its performance. It challenges architects to establish a negotiation between the environment and the built structure. Such concepts of sustainability can be seen in in power generation, solar radiation, and ecological infrastructure. Also, societies are progressing in the context of the growing usefulness of computation and technological innovations, it is changing our understanding of time lapses as they are becoming increasingly shorter (by development taking place). For example, development such as ubiquitous computing and mobile telecommunications are creating new ways to think about communities and the uses of public space by reshaping the definition of privacy or sacrificing some areas of privacy to gain other benefits. This calls for an understanding of sustainability in architecture in such a way that makes places sustainable over time.

This shifts our minds to think about architecture in a context amenable to temporal realities and change, by incorporating time as a design contingency. Generally, in architecture, designers think about functional performance and aesthetic values while freezing the time component resulting in a static fixed structure. A reaction to this way of thinking about sustainability over time is operating under a dynamic understanding for built environment on a long-term basis. Then how we can design for time?

In her interactive architecture 2005, Bullivant defined adaptability as "*to describe an interactive building via real-time changes through kinetic systems in response to environmental changes through variable mobility location and geometry*"[1]. This suggests incorporating an evolutionary system and new paradigms into the design that creates processes to evolve architectural form and to also allow for the appropriate means by which a structure may be objected to morphological changes. Thus, we start thinking about architectural typology as a narrative that adapts to its context and time frame. Hence, this shifts our perception of architecture as a static building to a constantly negotiating and adaptable structure by raising a question about generative strategies that allows evaluating performance, spatial quality, and fabrication process. More precisely, develop design input models that describe design intent to guide design adaptability.

"*To raise a question of typology in architecture is to raise a question of nature of the architecture work itself"*[2]. This thesis proposes a framework for adaptable architecture by embedded computational infrastructure as a simulation that can draw a logic for an implementation as an actual physical structure. This is achieved by first investigating theoretical precedents that challenge the definition of the conventional architecture as a static structure and incorporates a design process that allows adaptability (design for time), such as Yonna Friendman's Towards a Scientific Architecture and Cedric Price's the Fun Palace (concepts of adaptability through a participatory approach).

Second, evaluate generative strategies that draw a logical method for developing a practical design input for adaptability implemented in the early design process and initial inputs. This is divided into two sections: First, investigate early implementation of form finding that draws a logic from the theoretical precedents for an adaptable framework in its structure, such as Peter Eisenman's synthetic representations. Second, look at recent precedents that investigate a framework connected to the logic of the early implementations of form finding but in a simulation that can draw a logic to adaptable structure in form evolution strategies.

[1] Bullivant, Lucy. 4dspace: Interactive architecture. 2005.

[2] Moneo, Rafael. Oppositions 13. On Typology. 1978.

1 Background:

1.1 Adaptability and Responsiveness in Architecture.

Adaptable and responsive solutions can be discussed in architecture by the evaluation of the design process in its form and formal presentation. This creates an evolutionary system and new paradigms in the design, that creates an adaptation process to evolve architectural form and the appropriate means by which an architectural object may be objected to morphological changes. Hence in architecture, this aims to think about a transition between fixed objects and final realizations (built structures) to adaptive and extensive systems subjected to constant negotiation with context and time-based design rules and decisions.

In 1960's Archigram projected ideas of the walking cities and although these ideas were unrealistic they question the relationship of the built structure and its surrounding. Moreover, Yona Freidman's and Cedric Price's model discussed concepts of adaptability and changes through a participatory approach which will be discussed in the following section.

1.1.1 Yona Friendman, Towards a Scientific Architecture

In the 1960s and 1970s, there was a firm belief that technology could be a platform for social change and that vernacular architecture could be a model for a democratic and balanced environment. These ideas were translated through computer-aided participatory design.

Yona Friedman's Toward Scientific Architecture, presented a participatory model and a diagrammatic procedure translating his theories toward Utopian architecture situating the design as an informational process that stimulates the human behavior and new types of social organization in a participatory approach. This allowed reflecting peoples influence through real components for open-ended design formation. However, the influence is evaluated by Friedman's set of rules to resolve conflict in intervention. His process draws the computational logic of translating data and translating designer's criteria as a loop feedback between the digital and physical mediums. This creates a constantly changing relationship based on behavioral rules of the designer and the morphological development in the real world.

This draws attention to the framework between both mediums since the digital presents the rules set by the designer and the physical presents the morphological development and intervention. The behavioral process of formation that draws the logic of translation between the two mediums should be able to investigate the constantly shifting behavior as an open-ended mechanism. This can be reflected in a fabrication process that constantly evaluates each procedure and design translation from the digital to the physical as well as by setting up the environment to track changes and translate back from the physical to the digital interface (feedback loop).

Friedman focuses on the participatory approach that creates the technical infrastructure, a goal for providing an extension for the public platform as well as providing a participatory democracy. This was achieved by introducing the FALTWRITER as a computer application that collects individual (the user's) desires and create a placement in the structure by resolving all conflicts in the inputs (desires). However, it sheds the light upon a process beyond the conventional one of design and construction by blending the edge between both digital medium and the physical, by design rules defined by the architect.

Figure [1]: Yona Friedman, *Eiffel Tower*, 1960

1.1.2 Cedric Price. Fun Palace

The fun palace challenges the conventional architecture as static building by synthesizing a wide range of temporary theories and discourse in cybernetics, information technology and game theory that is highly adaptable to the shifting social and cultural condition of its time and place, presenting it in scaffold structure enclosing these conditions.

This definition of not presenting architecture as static and solid building, but as an active and dynamic spaces that constantly adapt to changes, by networking multiple events and space oscillation between activities. Spaces should be endlessly varied in size, shape, lighting and accessibility.[3]

It started by considering the architecture as problem not of static structure but that can be described in constant activities of continuous process construction. *In a sense, it was the realization of the long unfulfilled promise of Le Corbusier's claims of a technologically informed architecture and the 'machine for living'. It was not a museum, nor a school, theatre, or funfair, and yet it*

[3] Mathews, Stanley. The Fun Palace: Cedric Price's Experiment in Architecture and Technology

could be all these things simultaneously or at different times[4] As it also can be a representation of architecture that can never be finished, presented in different programs. *The variable ''program'' and form of the Fun Palace were not conventional architecture but much closer to what we understand today as the computer program: an array of algorithmic functions and logical gateways that control temporal events and processes in a virtual device*.[5]

This architecture is conceived as a tool more than a building since it is responsive to the users need, raising the question what kind of responsiveness this architecture offers, since it's already defined by Price and Littlewood programmatic features. The fun palace offered the responsiveness as a feedback system that allows the control of the user, creating architecture in suspended animation full of possibilities yet to be realized, thus its incompleteness seems potent.

This changing status of the building was actuated using frames (structural framework) and a crane (analog), this allows the possibility to translate the space into an innumerable generation of actions under the participatory purpose of the users.

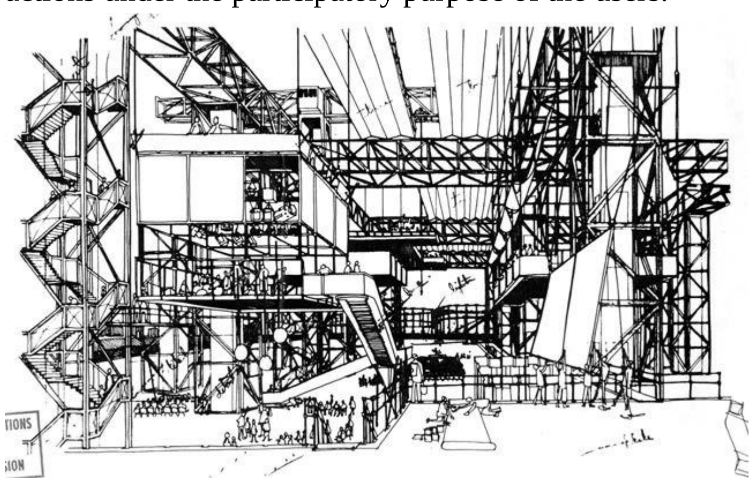


Figure [2]: Cedric Price. The Fun Palace

[4] Mathews, Stanley. The Fun Palace: Cedric Price's Experiment in Architecture and Technology
[5] Mathews, Stanley. The Fun Palace: Cedric Price's Experiment in Architecture and Technology

1.2 Models of Adaptation and states of Representations for Morphological Changes

Friedman's and Price's model represent a theoretical base for architecture adaptability in participatory approach. More precisely, Price's model suggests frames/scaffolding as a structure to actuate his model, however, these models are theoretical and conceptual. This section will focus on design schema's models that allows adaptation process, more precisely, explore models that breaks the static state of built structure in its form and also explore models of formal presentation that sets the design schema into motion and morphological changes. Thus, to allow morphological changes in architecture, the evaluation of adaptation models are important.

Since this research will focus on the adaptation possibilities in the digital interface, it is important to create a model that allows translation of design methods and adaptation process to take place.

1.2.1 States of Representations (Early Implementations)

This section methods provides a link between design process and form finding through morphological changes. This approach might provide a link between process and an integrative behavior-based process to develop dynamic specific architectural system interrelated in their material, spatial and environmental nature, rather than a design process that can be incorporated in form finding, data collection, and analysis method.

The following early cases of implementations define a process of adaptation and morphological change using specific representations. However, this process is distinct and separate from the physical built structure in terms of material and morphological changes process, such process of form finding did not account for physical and space constraints of the final built structure when processed.

1.2.1.1 Peter Eisenman. House of Cards (VI)

From the late 1970s to the 1980s, Peter Eisenman demonstrated his ideas in series in houses, developing architecture not only based on function but simulated by a formal structure of language investigating the meaning of architectural form. Specifically, through a process of transformation moving beyond the cube formation to more complex and divided volume. Embracing representation phases of architecture, by layering operation (here layering is understood in form of fragmenting) and it contributes to understating complex forms and generates spaces that communicate the design process. This will consider the building as a formal system of varied elements by defining the relationship between them.

The design emerged from a conceptual process that began with a grid. Manipulating the grid in multiple sections of the house, this operation creates a three-dimensional space by overlapping spatial layers, approaching the layers as a structural operation resulting in architecture recording the design process.

Thus, this process is concerned with conceptual and formal uses, and produces an architectural form (spatial layering). This process allowed breaking down the spatial quality and the architect's main schema to evaluate the morphological behavior of design. However, this process is still bounded as part of the conventional design process and does not bridge the process itself and the physical structure. The process ended with the structure built.

In his book The New Paradigm in Architecture, Charles Jencks defines "layering and ambiguity" as one of the experimental "movements" of Post-Modern space that "develops the ambiguity and complex spatial layering – the skews, shifted axes and dissonant figures" in the 1970s. This movement, as Jencks calls, "*leads into the movement of folding, blob architecture and biomorphic design, all aided by the computer" from 1985 then on*.[6] Regarding this process, it appears layering a design schema allows design modification and formation relative to the architect's rules

[6] Jencks, Charles. New Paradigms in Architecture. 1970.

and definitions (in Eisenman's case it is spatial quality). This proceeds to question the criteria of this relationship that can be expanded to a real physical context.

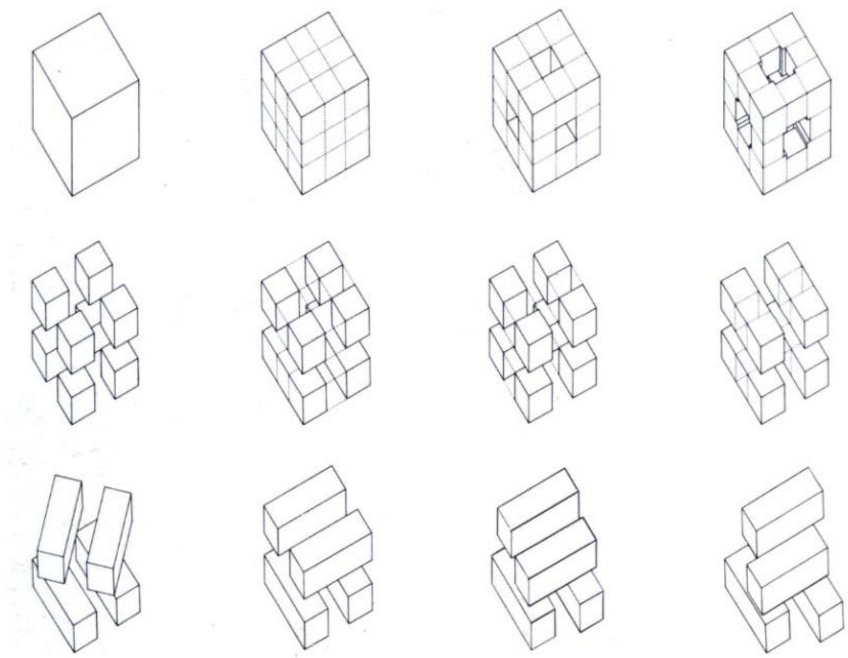
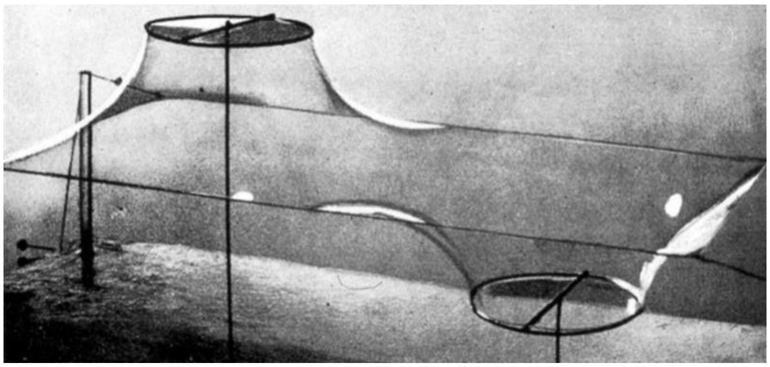


Figure [3]: Peter Eisenman. House (VI) Representation.

1.2.1.2 Frei Otto, Connecting and Occupying.

Frei Otto and the Institute for Lightweight Structures in Stuttgart investigated the optimized path systems; experimenting with material and/or modeling techniques to calculate form like Gaudi's chain model for Sagrada Familia. It was achieved by testing material behavior and introducing one material with another, creating a transformation of the material condition. These materials restructure themselves within interaction and with applied forces for "form finding". In his tests, involved techniques on material and frames such as soap bubbles and metal chains, allowing procedural transformation resolving a geometry that is derived from a complex behavior born from the constant negotiation or optimized with the forces projected, we can relate to it as a form of analog computing. The flexible framework of the material and techniques suggest integrative design strategies and synthesis with the physics of the material used.

In his book; *Connecting and Occupying, 2009*[7], Otto underlies the process of formation and morphology through his methods using material and geometric logic. Thus, we can think about a possibility to create such a framework in architecture design that allows this constant change while simulating a physical force for architectural form generation.



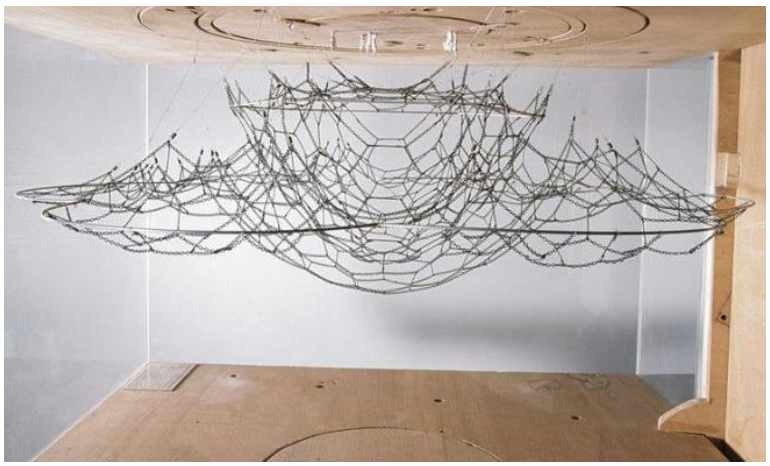


Figure [4] top: Frei Otto Soap Bubble Experiment
Figure [5] bottom: Frei Otto. Hanging Chain Model

[7] Otto, Frei. Occupying and connecting. 2009.

1.2.1.3 John Frazer. An Evolutionary Architecture

In his book An Evolutionary Architecture 1995[8], Frazer investigates form-finding generating processes in architecture with a theory of morphogenesis in the natural world by creating simulation models that respond to the changing environment, using genetic algorithms to create genotype whose fitness is closest to the values intended.

One of his experiment in 1993 infers from solar radiation, by creating an initial form while its elements (genotype) grow or move to protect the surface from solar radiations (specified by using the three-dimensional cellular automata controlled by genetic algorithm). This results in a formative process instead of explaining the form by reflecting a bottom-up process in form finding and how it might replace a top-down one.

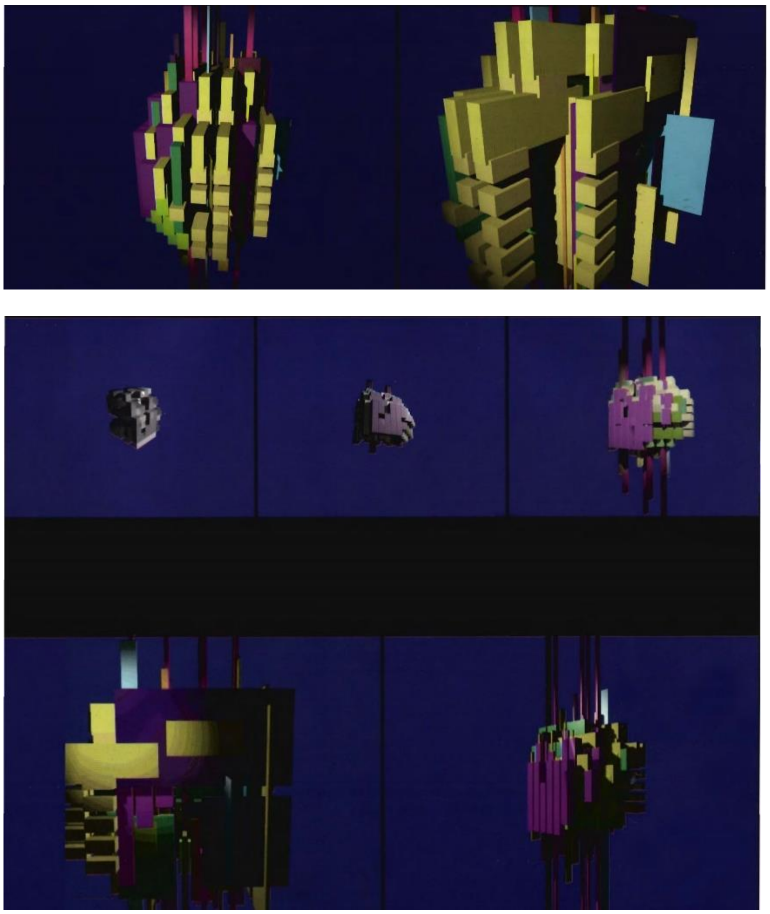


Figure [6]: John Frazer. An Evolutionary Architecture. Generative Sequence Tomas Quijano and Manit Rastogi, 1994

[8] Frazer, John. An Evolutionary Architecture. 1995

1.2.2 Models of Adaptations (Recent Work/Precedents)

From Otto's model, we can reflect that the designs produced by the tool should be valid in the language defined by that tool or synthetic representation (Eisenman's model). If those designs are to be evolved using a genetic algorithm, the operations on them must retain their shape grammar generated nature. In other words, every design in every population during the evolutionary process must be a valid design in the language. Such model allows for a complex investigation to take place, while other capacities as design or environmental rules (e.g. gravity in case of Otto's hanging chain model) offer the possibilities to investigate the modeled system.

The general question arises of what methods and design schemas allow their emphasis to be on the evolution of behavior through the translation of the designer rules and physical world parameters, rather than on design complexity, such as geometry and spatial quality? And it must be taken into consideration that this model should be translated through into the physical world (future step).

1.2.2.1 Michael Fox. Interactive Architecture.

In his book Interactive Architecture 2016. Fox explores precedents in interactive architecture as intelligent responsive systems that allow negotiation between both the system and its environment, precisely mediating human interactions and environmental forces with built structure. *The goal is designing and building environments that address dynamic, flexible and constantly changing needs.*[9] . These structures imbedded computational, kinetic and mechanical systems to manage environmental and human interactions as inputs and mediate the behavioral output accordingly.

From his book we will explore two different precedents in interactivity. The most important concentrates on input strategies that allows adaptation and response operating on molecular level

[9] Fox, Michael. Interactive Architecture. 2016

(singular element) creating interactive response in collective behavior (sum of parts).

MegaFaces by Asif Khan.

MegaFaces designed by Khan is a pavilion built at the Sochi winter Olympic and Paralympic games, in 2014 for MegaFon. It represents facial expression created on a kinetic façade that enables participants to display their faces in 3D structure on it at 3500% magnification.

Relayed on kinetic façade and multi-camera 3D scans, the scan will be translated to the pavilion kinetic façade composed of actuators that protrudes for a specific distance, collectively composing the structure of the scanned face. The most important part is the fully equipped actuators that can extend out allowing transformation in 3D space, operating from singular actuators as molecular level to collectively create the topological structure of the faces. 11,000 actuators have been used to create a high-resolution representation of the topological structure of the scanned faces.

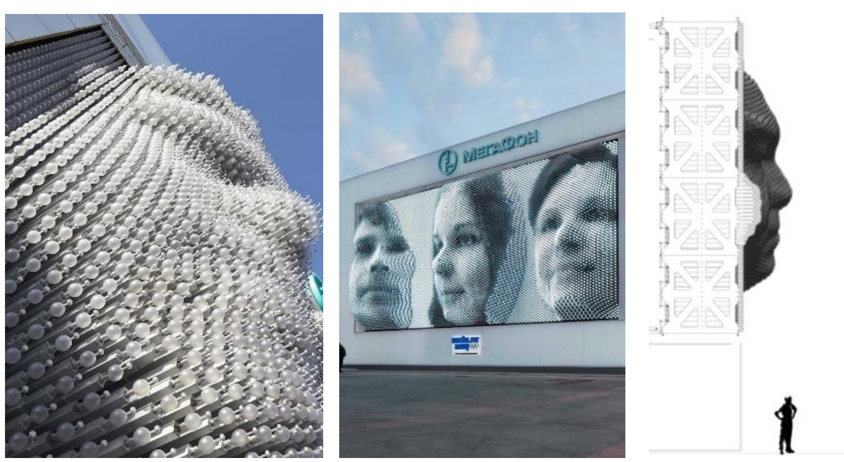


Figure [7]: Mega Faces by Asif Khan. 2014. Megafon pavilion at Sochi 2014 winter Olympics, Russia.

Reef by Rob Ley and Joshua G. Stein.

Reef structure remodels architectural envelope using technology to immune spaces with behavioral qualities. Using emerging material technology, it reprograms the architectural envelope and its role towards the context as an interactive envelope.

It focuses on defining emerging structure by using Shape Memory Alloy (SMA); a category metal that changes shape according to temperature used as material technology, as a singular element, it allows the logic of nature to move beyond the formal mechanized motion paralleling the lower level organism (reef) in its responsive motion. The user interaction within the structure space allows changes to occur on each part of the alloy (molecular level) results in a collective behavioral with a fin pattern allowing the space to selectively open (collective behavior) and creating local moments of visual transparency.

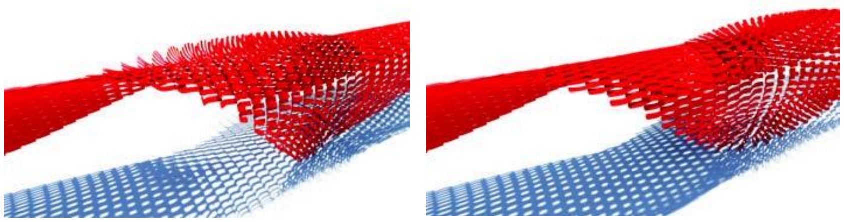


Figure [8]: Reef by Rob Ley and Joshua G. Stein. New York City. 2009.

1.2.2.2 Stefan Krackhofer Form evolution - Organised Spatial Distribution based on Voronoi Information

The approach states a computational geometry of Voronoi diagrams for generating spatial effects enabled through simulation of space, material, light or behavior in architecture resulting in a simulation rather than a spatial representation. The implementation started with a space filled with Voronoi diagram, by dividing it into subspaces according to object distribution specified by the designer, such as each Voronoi space defines spatial adjacency in relation to the objects presented, creating spatial relationships.

Using agents to occupy the space created by the Voronoi cells according to design values specified through this simulation such as distance, brightness, and height. This experiment reflects on *"Architecture to create complexity and space. As such, collecting and processing of information becomes an important part of computable space in order to make and support decisions and consequently to change, adapt or manipulate space"*[10]

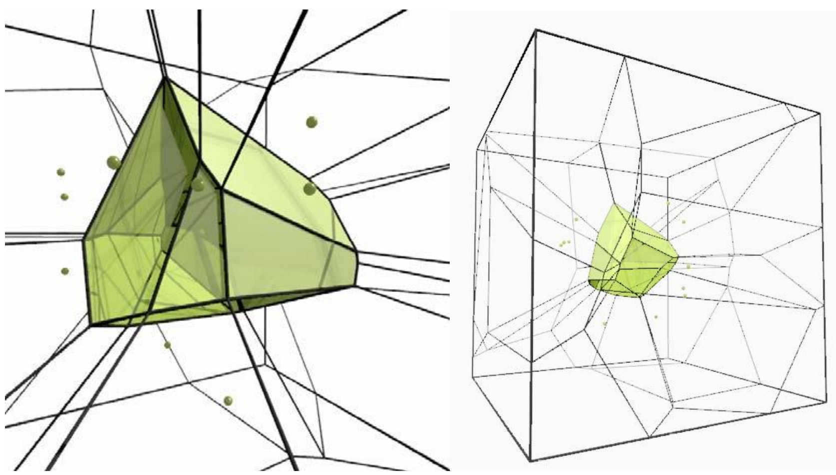


Figure [9]: 3D Voronoi Spatial Simulation, 2005

[10] Krackhofer, Stefan. Generating architectural spatial configurations. Two approaches using Voronoi tessellations and particle systems. 2005

1.2.2.3 Mustsusru Sasaki. Digital Transformation into Structure

In 1998 Sasaki had experienced “organic inspiration of seaweed transformation” digitally into structure in Sendai Mediatheque project by Toyo Ito. This was achieved by a process of creation of organic forms. His structure design methods were focusing on shape optimization and analysis for generation of free curved shells in which was based on sensitivity analysis as fitness value. He applied this method as well on Kitagata Community Centre designed by Arata Isozaki. However, this method was based on analyzing the structural efficiency of a shape produced by the architect. In 2003 Sasaki was able to produce a shape which would be designed with efficiency in mind rather than optimizing the architects input, referring to banyan tree as his design inspiration for a performative form (base of representation) , he operated the analysis and shape production by carrying out extensive matrix operations using the three dimensional Finite Element Analysis (FEM), the algorithm starts to evolve into a static congruent shape, giving an optimal solution as an emergent project.

Figure [10]: Arata Isozaki and Mutsuro Sasaki, Qatar National Convention Centre in Doha, 2008

1.2.2.4 Orestos Chouchoulas. Shape Evolution

Shape Evolution is presented as a design method and a tool supporting initial stages of architecture design, the aspect of his work is creating a link between genetic algorithms and shape grammars. In the shape evolution process the architect introduces his own shape grammar as generators of the design, resulting in its own genotype as a vehicle for aesthetic values, while the genetic algorithm optimization is respect to the structural performance "*The key interface between the shape grammar and the genetic algorithm is a string that encodes the sequence by which shape grammar rules have been applied to generate a given design*"[11]

The case study presented in an apartment building which dwellings are associated with circulation blocks (open orange framework). Shape grammars associated with apartment block/dwellings and circulation blocks are used to devise possible association with elements (functional distribution), while the genetic algorithm generates a solution to conform with the design decisions specified by the architect; such as the ratio between circulation and dwellings, or balconies views are presented in the case study.

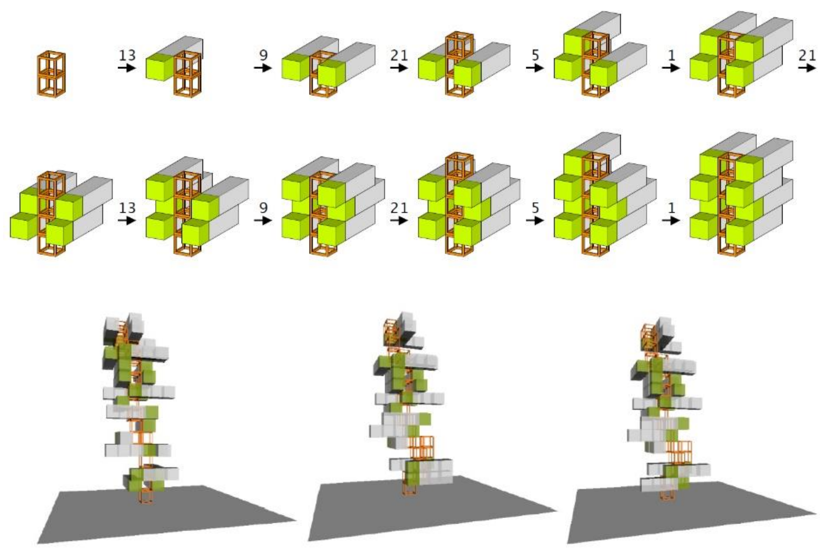


Figure [11] (Top): Sequence of generation for an apartment using the grammar.
Figure [12] (Bottom): Tower Design with Maximum Scores

[11] Chouchoulas, Orestes. Shape Evolution: An Algorithmic Method for Conceptual Architectural Design Combining Shape Grammars and Genetic Algorithms. 2003

1.3 Generative System and Design Schema's Representations

In behavioral-based approach; more precisely: morphological changes, the elements of the system include the processes, physical constraints, and influence of operation that allows them to be translated. Design schemas result from the resolution of the various behaviors by their ability of adaptation in terms of their geometric position and the information (design decision and data) that defines its state as a simulation model.

Generally, we can initiate representations for design schema that enhance adaptation process and morphological changes. But would this representation by itself be efficient to represent the original schema? On a different note, would one representation be efficient to translate the design intentions and physical quality of the original design schema?

It is important to reflect physical and design quality processed from these schemas when initiating one or multiple representations creating a complex formation of the design required. De Landa argues that complex formations emerge when material negotiates differences in intensity. *When such negotiations take place in "far-from-equilibrium" conditions, they enable emergence of the "full variety of topological form"* [12].

Thus, *a system as a whole is not an object but a way of looking at an object. It focuses on some holistic property which can only be understood as a product of an interaction among parts.*[13]

[12] De Landa, Manuel. A Thousand Years of NonLinear History. 2000
[13] Alexander, Christopher. Architectural Design Theory. 1968.

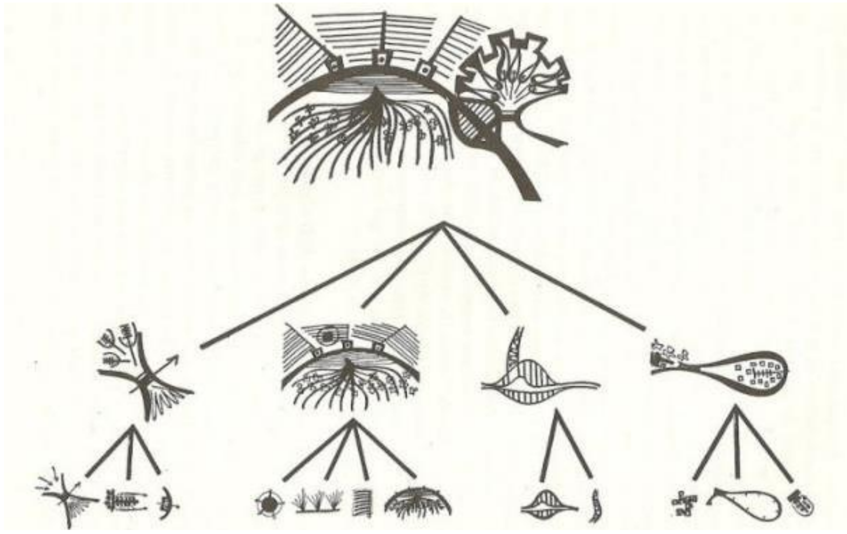


Figure [13]: Kit of parts. Notes on Synthesis of Form. 1964

More Specifically, when multiple representations of an object or design schema occur in the same space, it is important to analyze the behavioral affordances of each of these representations since it is not simple to establish a negotiation between structural performance, materials, environment variables and functional intentions without understanding the implications of these behaviors. Thus, there is a necessity to think about a generative system in its component levels to produce several efficient solutions that could contribute to the complex shapes of the architecture while adaptation processes are used to evolve the architectural form generated by these components. *A generating system is not a view of a single thing. It is a kit of parts, with rules about the way these parts may be combined*.[14]

[14] Alexander, Christopher. Architectural Design Theory. 1968.

1.4 Raising the Question

It is important to question a framework that allows adaptation and growth that integrates architecture as a complex and adaptable system, proposing structures to be conceived as intelligent entities capable of resilient and morphological change. This guides us to think critically about the generative system that allows evaluating performance, spatial quality, and fabrication process in architecture. More precisely, developing a design input model that describes the design intent that will guide design generation.

This thesis investigates and proposes a framework for architectural design that allows adaptation and morphological changes in design schemas. More precisely, it investigates representations that break the static conditions of any design schemas allowing morphological changes. This form the concept of a responsive architecture allowing us to gain more control over our increasingly unpredictable circumstances and design interpretations that is critical for its sustainable development.

The question arises: which models of representations allows translating design and ecological rules for fundamental morphological changes and adaptability in built structure? More precisely (research question):

Can a simulation environment bring to light the specific geometric affordances of voxels and Tetra Meshes in a way that enables morphological changes that suggest this adaptiveness?

2 Hypothesis

The hypothesis introduces aesthetics and explicit discourse of form in design schemas through topological representations that might enhance its adaptability and allow morphological changes of its structure. Specifically, utilizing design schema's topological representations in Voxels and Tetra-Meshes.

These representations break the rigidity and blur the boundary of the design schema, allowing adaptation to design rules and processes while enhancing its flexibility and adaptability to reflect morphological changes, where the discourse of voxels and tetra-meshes will inherent in the object as a type that developed over time.

The notion of these representation is to make use of dynamically and generative parametric methods and apply them as a configuration of the design, the figurative aspects of the source schema become less important while the overall notion of the resulting representation will still be maintained. The rational criteria implied for the use of voxels and tetra-meshes is their ability to fulfill structural integrity and fabrication process as next steps for this thesis.

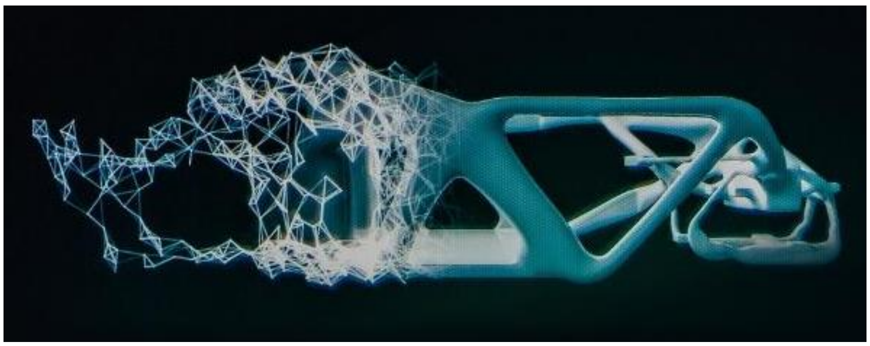


Figure [14] : Maurice Conti: The incredible inventions of intuitive AI | TED Talk. *This image goal to represents the mesh of the original design schema.*

3 Methods

The prototype goal is to investigate an evolution-based generative design system, using topological representations for design schemas. Randomness is introduced as a major driving force in mechanisms of adaptation such as those present in several natural and artificial systems. The introduction of a randomized procedure like genetic algorithms (Frazer's form finding generative process[15]), aiming at introducing non-deterministic process into the system and represented a move towards the adaptation paradigm. This view puts an emphasis on action and behavior instead of a simple reaction to proposed parameters. Thus, a crucial part is the creation of such rules and representations to generate alternative design models allowing an appropriate level of variability.

The question arises: Given an initial schematic proposal for building, how would its overall 3D geometry adapt to external forces and designer evaluation?

Creating a discrete representation to a schematic proposal might result in the generation of topological representations that allows adaptation mechanism and morphology. For this strategy, the space partitioning and slicing generative design method can be employed to create two schemas: Voxels (n-dimensional pixels) and tetrahedral meshes representation. These schemas allow incorporating an appropriate level of variability into the encoded geometry (3D object).

Generally, the computational method consists of two phases:

- A generalization phase to encode the design schema into voxels and tetra meshes.
- The specialization phase to evolve a specific morphological order using the encoded schema using

[15] Frazer, John. An Evolutionary Architecture. 1995.

Cellular Automata and L-System, both represent the set of rules the designer encodes as design variability and parameters. However, the important factor is the affordances of each schema encoded (voxels and tetra mesh) in an application.

The goal of adaptation: The objective to test the differences of affordances between the structural essays, resulted from self-regulatory morphological order, this allows speculating on architecture design strategies containing these orders and analog systems that synthesize between the encoded schema of models.

3.1 Cellular Automata (CA)

A grid-based method can be found through cellular automate the application, each cell can be in two conditions: on-off / live-dead. Such cellular automata generate patterns rather than form, and this is important aspect since we start with initial design schema while experimenting morphological changes using encoded rules. The pattern of the CA may consist of any configuration of live cells, and at each step all cells area update. It reaches its final pattern after a predefined number of cells or when the desired pattern is produced (relates to design decisions).

3.2 Lindenmayer system (L-System)

Lindenmyaer system, known as L-system, presents plant morphologies process. In which virtual plant genotypes are inspired by the mathematical aspect of the system. The phenotypes are the branching structures resulting from the derivation and graphic interpretation of the genotypes. Evolution is simulated using a genetic algorithm with a fitness function, suggesting that artificial evolution constitutes a powerful tool for exploring the large, complex space of branching structures found in nature while generating a novel one. The notion of using an L-System is testing the prototypes within generations treated as continuous (branching) in contrast to the gridded cellular automata structure, as well as in the use in the prototype to compare affordance and applicability of the system used in different representations as a design rule.

3. 3 Prototype

3.3.1 Generalization Phase

Encoding design schema into the following:

- Tetra Meshes
- Voxels (fixed size unit)
- Voxels(octree)

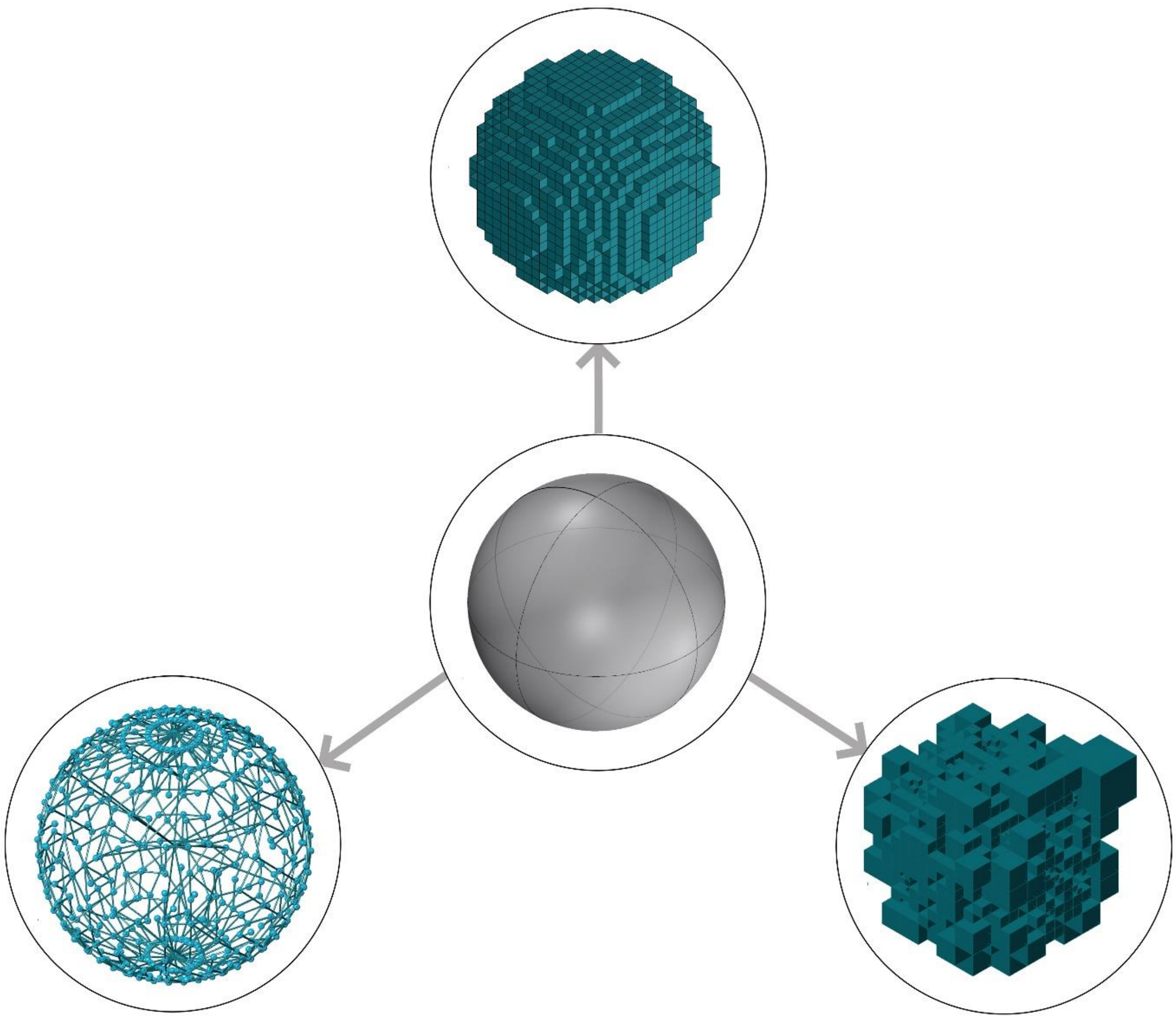


Figure [15]: Initial Schema Representation (Sphere was selected for initial schema) in Voxels (top), Octree Voxels (bottom right), and Tetra-Meshes (bottom left)

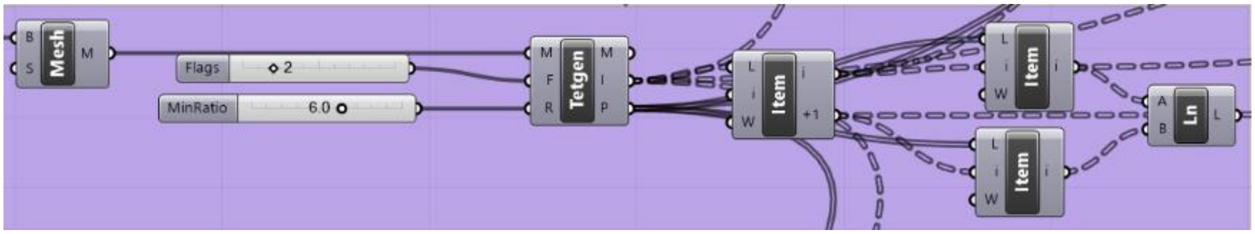


Figure [16]: Tetra Mesh Generation

Tetra Mesh Generation: transforming a geometry to mesh, TetGen generates exact constrained Delaunay tetrahedralizations, boundary conforming Delaunay meshes, and Voronoi partitions., generating list of points(P) and group of 4 edges (I)TetGen is executed at the Weierstrass Institute for Applied Analysis and Stochastics in the research group of Numerical Mathematics and Scientific Computing.

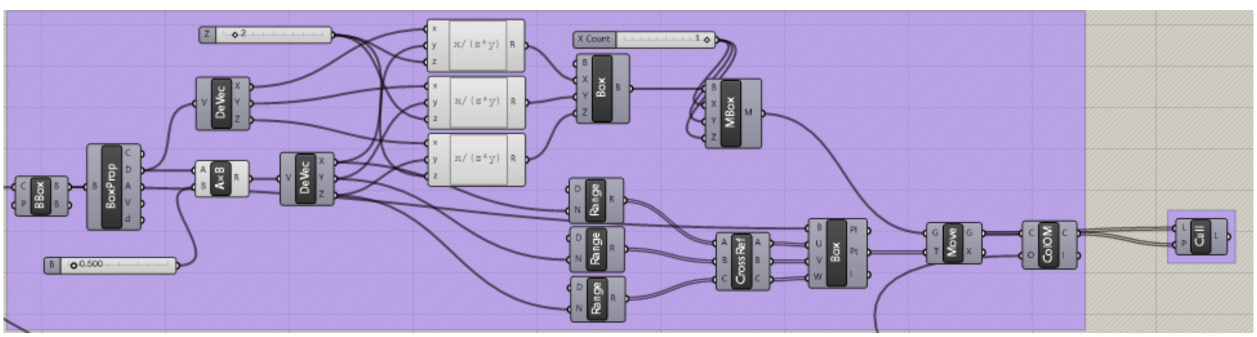


Figure [17]: Voxels Generation

Voxels Generation: evaluate the diameter of the geometry bounding box, by the ratio of its length as an integer for voxel dimension. The first part of the operation is creating a bounding box full of voxels, the second part is evaluating the main geometry and the voxels created and visualizing the resulting intersection resulting in voxel representation of the geometry.

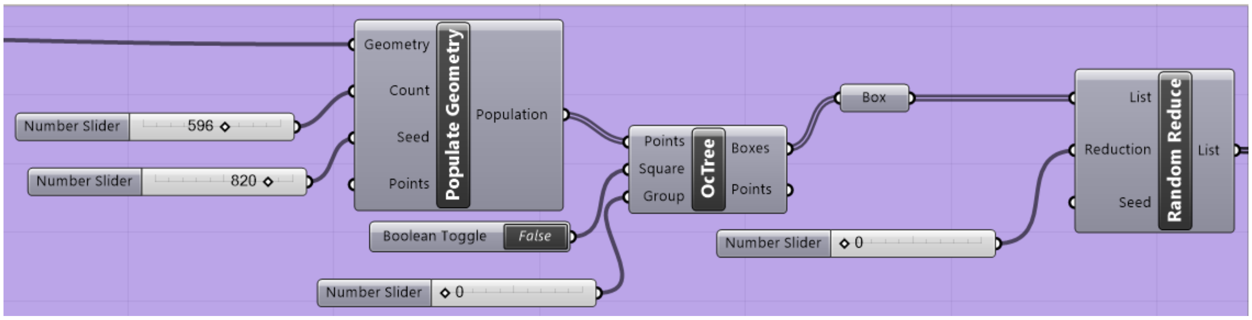


Figure [18]: Octree Generation

Octree Generation: use populated geometry to create (1) amount of points in the geometry and the seed random insertion in the geometry. (2) use (points) to add points generated from the voxels and reference for the octree generation. After this step the points generated are passed to the grasshopper component (Octree) to create the octree squares, with the (group) input to define the resolution of the octree by grouping points.

3.3.1.1 Representation Resolutions

It is crucial when working with the Voxels, Tetra Meshes, and Octree to allow specific amount of control point that can enhance topological structure or the amount of control point, such approach might allow more intricate and specific design evaluation and mutation. These resolution strategies were translated in each representation as the following:

- Tetra Meshes resolution: increase the number of vertices inside the surface created (solid space), this will allow more control points, increase number of edges, and allow better connectivity between the vertices.
- Voxels resolution: increase the number of voxels and reduce the voxel unit size, such thing will allow better topological representation for the original schema and more count of voxels.
- Octree resolution: reduce the larger voxels and increase small dimension voxels.

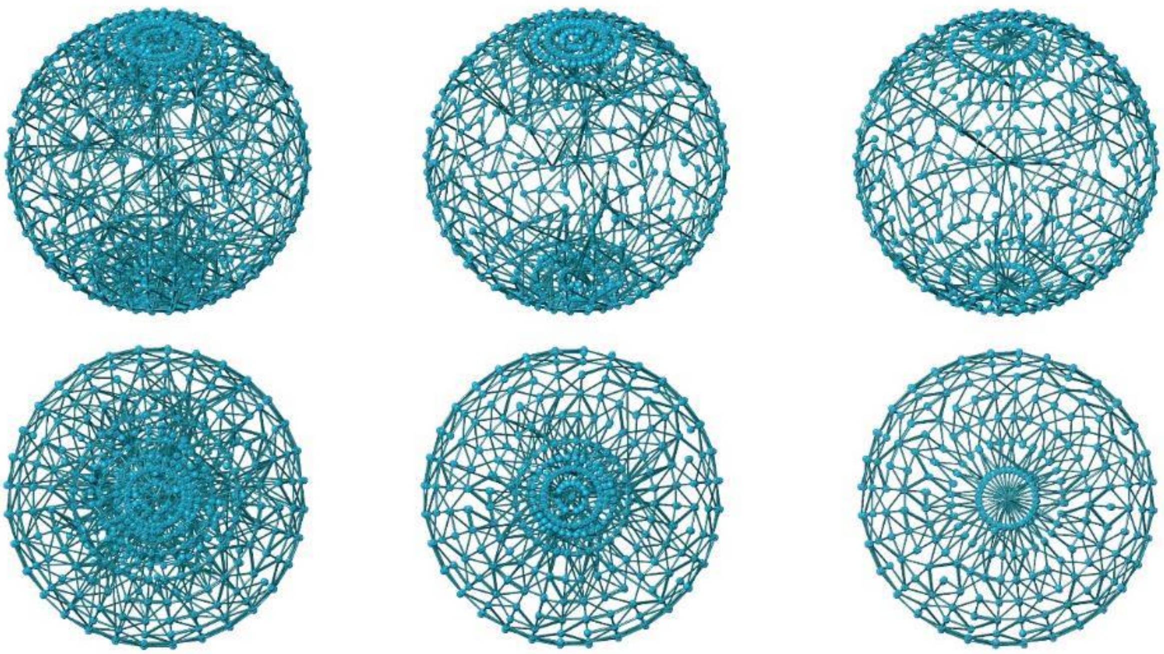


Figure [19]: Mesh Resolution. Perspective View (top) Plan View (bottom)

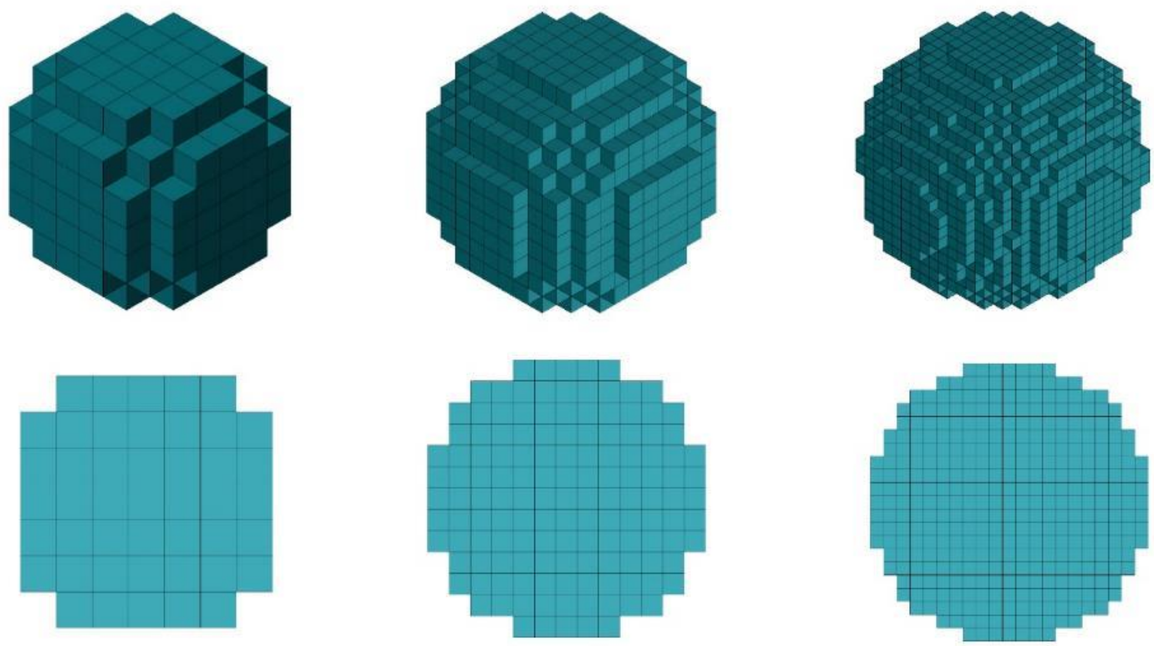


Figure [20]: Voxels Resolution. Perspective View (top) Plan View (bottom)

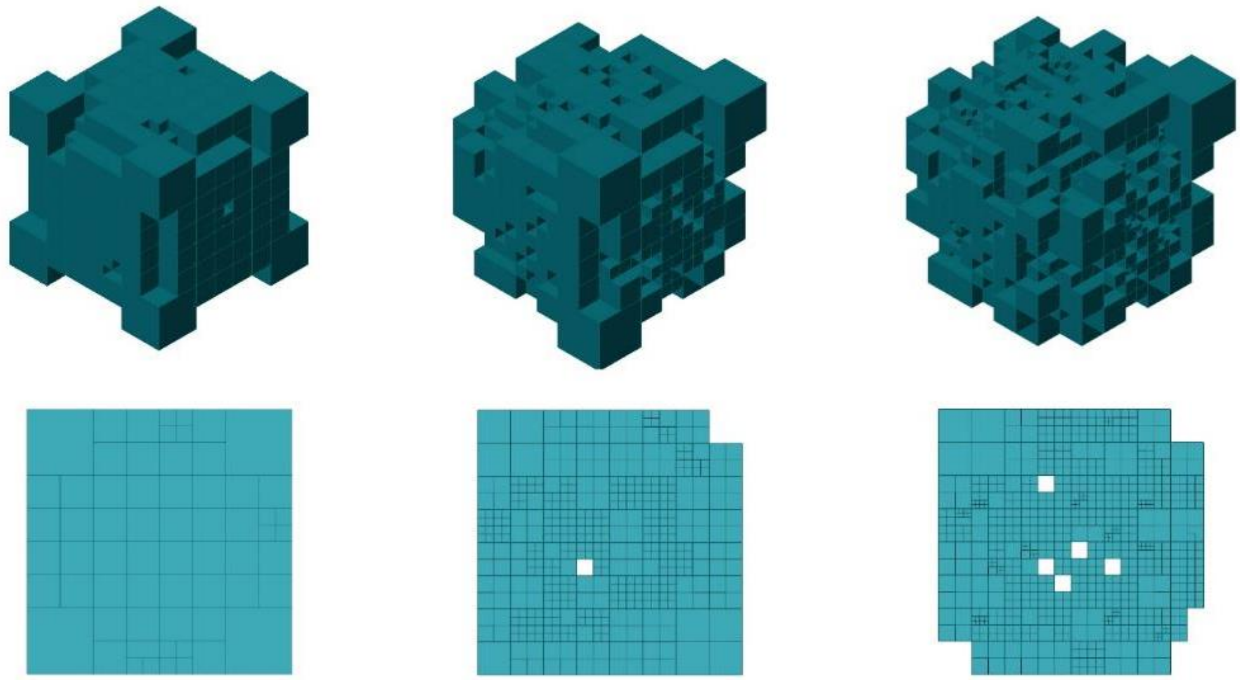


Figure [21]: Voxels(Octree) Resolution. Perspective View (top) Plan View (bottom)

3.3.1.2 Attractor in Representations

The attractor is a metaphor for a constraint in the design environment, its contribution in both Cellular Automata and L-System on defining closest points in the representation. In CA, the voxels and vertices in meshes included are closest to the attractor and are fixed components and contribute as a value (of being alive/dead) to all other cells. This is a constraint that is added to each voxel/vertex in the representations when calculating each cell state. In L-System, the selected parts are the branching starting point.

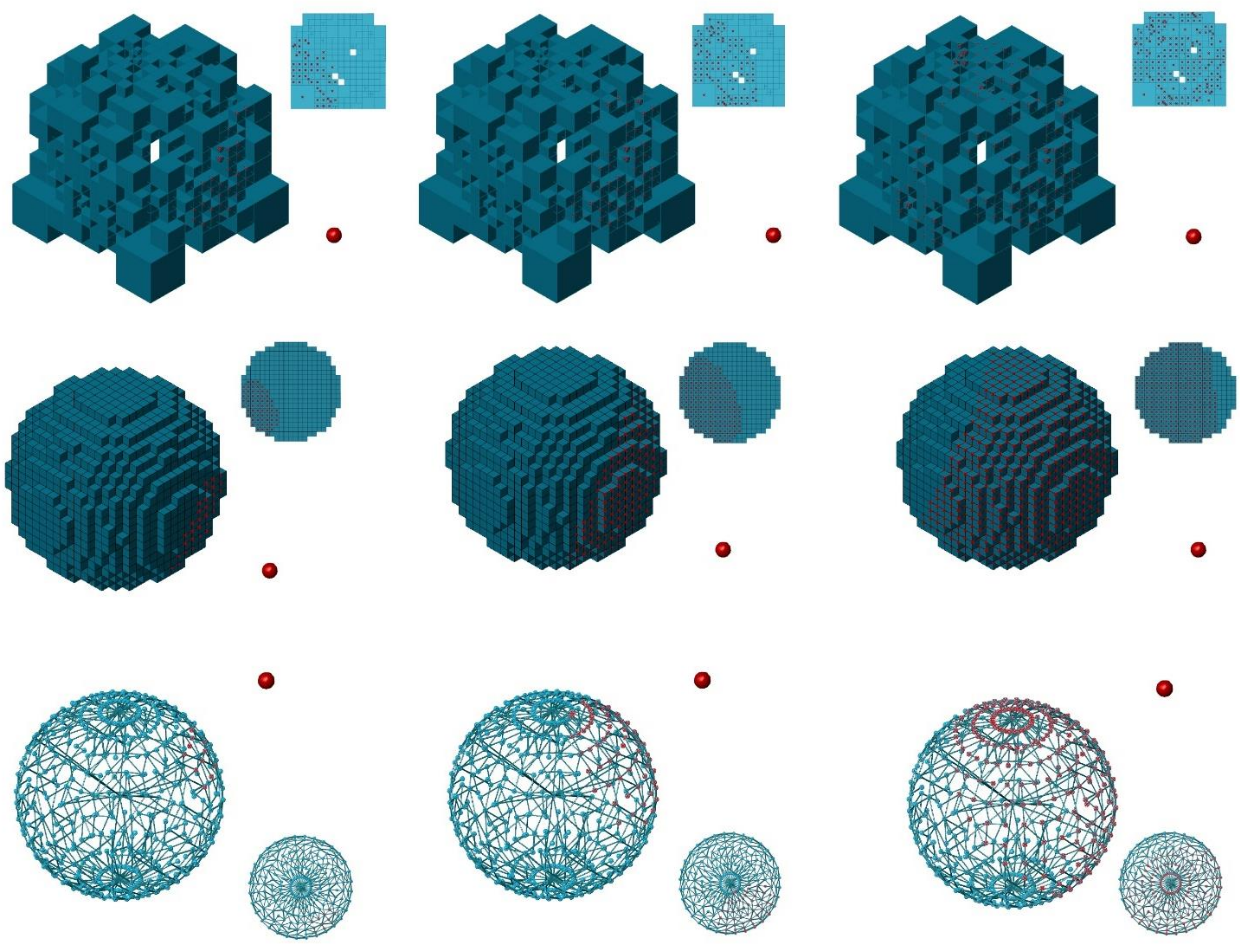


Figure [22]: Attractor's relation to representations (red dot). The shortest distance can change. Each representation with its relevant attractor plan (increases from left to right)

3.3.2 Specialization Phase

3.3.2.1 Cellular Automata

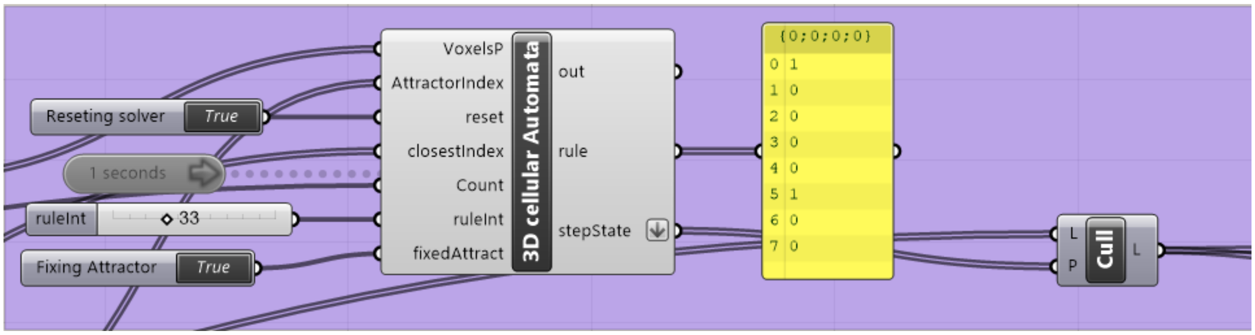


Figure [23]: Cellular Automata (CA)

Define parameters for the CA code as the following:

- *VoxelsP*: all voxels center points.
- *Attractorindex*: index of voxel cells effected by the attractor.
- *Closestindex*: index of voxel cells that are closest to voxel operated
- *Count*: define the number of neighboring cells.
- *ruleInt*: the CA rule as an integer to be calculated into Binary (0/1, Dead/Alive).
- *fixedAttract*: Boolean (True/False) if the attractor points should be fixed changed in status (Dead/Alive)

With these definitions, the *ruleInt* will be transformed into 8-digit binary in the code, and each cell has a counter represented as integer that keeps increasing (related to neighboring cells plus Attractor Cells) while CA is running. Each phase this integer will be hashed into the binary number to evaluate the cell status.

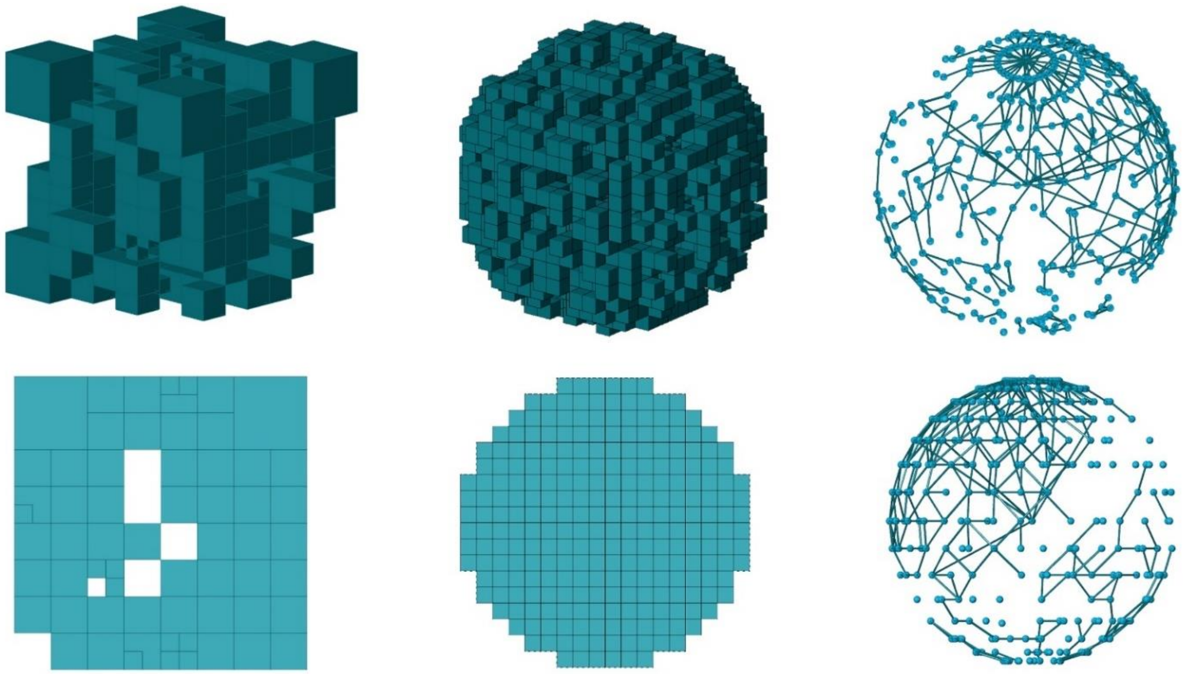


Figure [24]: Cellular Automata rule integer (90). Binary Rule conversion to 8 digits (01011010). *Each voxel/vertex calculates its neighbor cells (according to distance) and attractor cell. The measured number of live/dead cell is considered a hash number to choose the condition status from the integer rule specified (translated to 0/1) (from right to left: Octree/Voxels/Tetra-Mesh)*

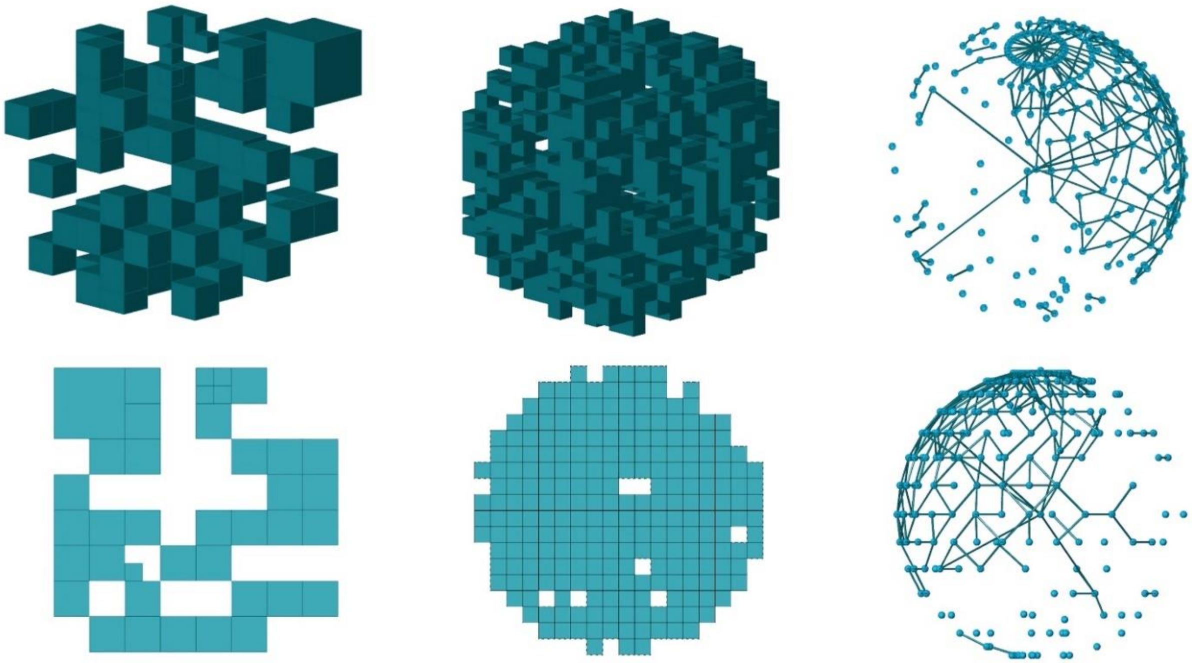


Figure [25]: Cellular Automata rule integer (30). Binary Rule conversion to 8 digits (10000100). *Each voxel/vertex calculates its neighbor cells (according to distance) and attractor cell. The measured number of live/dead cells is considered a hash number to choose the condition status from the integer rule specified (translated to 0/1) (from right to left: Octree/Voxels/Tetra-Mesh)*

3.3.2.2 Lindenmayer System (L-System)

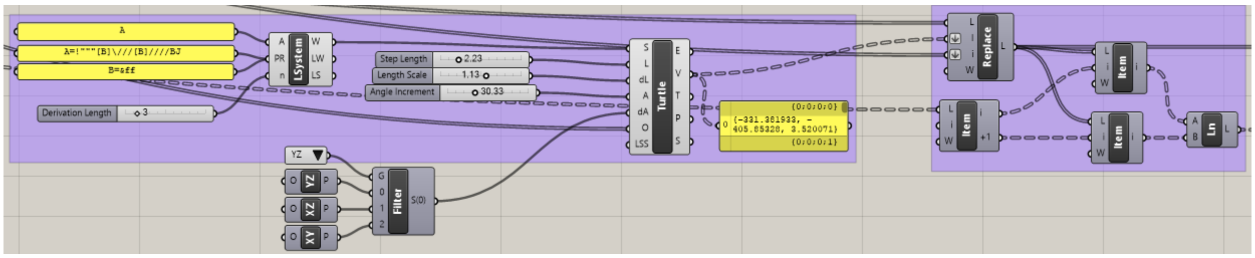


Figure [26]: Lindenmayer System (L-System)

Points resulted from the attractor component will be the base for the L-system. First by defining the gene and the amount of generation, they will be passed to the component that directs the path of the element according to the gene, angle and length of step required.

In the Mesh implementation, vertices and edges are reevaluated to create the stretching effect without breaking the Mesh structure. In the voxels implementation, the voxel dimension is evaluated for stacking effect, this allows voxels stacking without collision at specific L-system *angle increment* according to the user's definition using the slider.

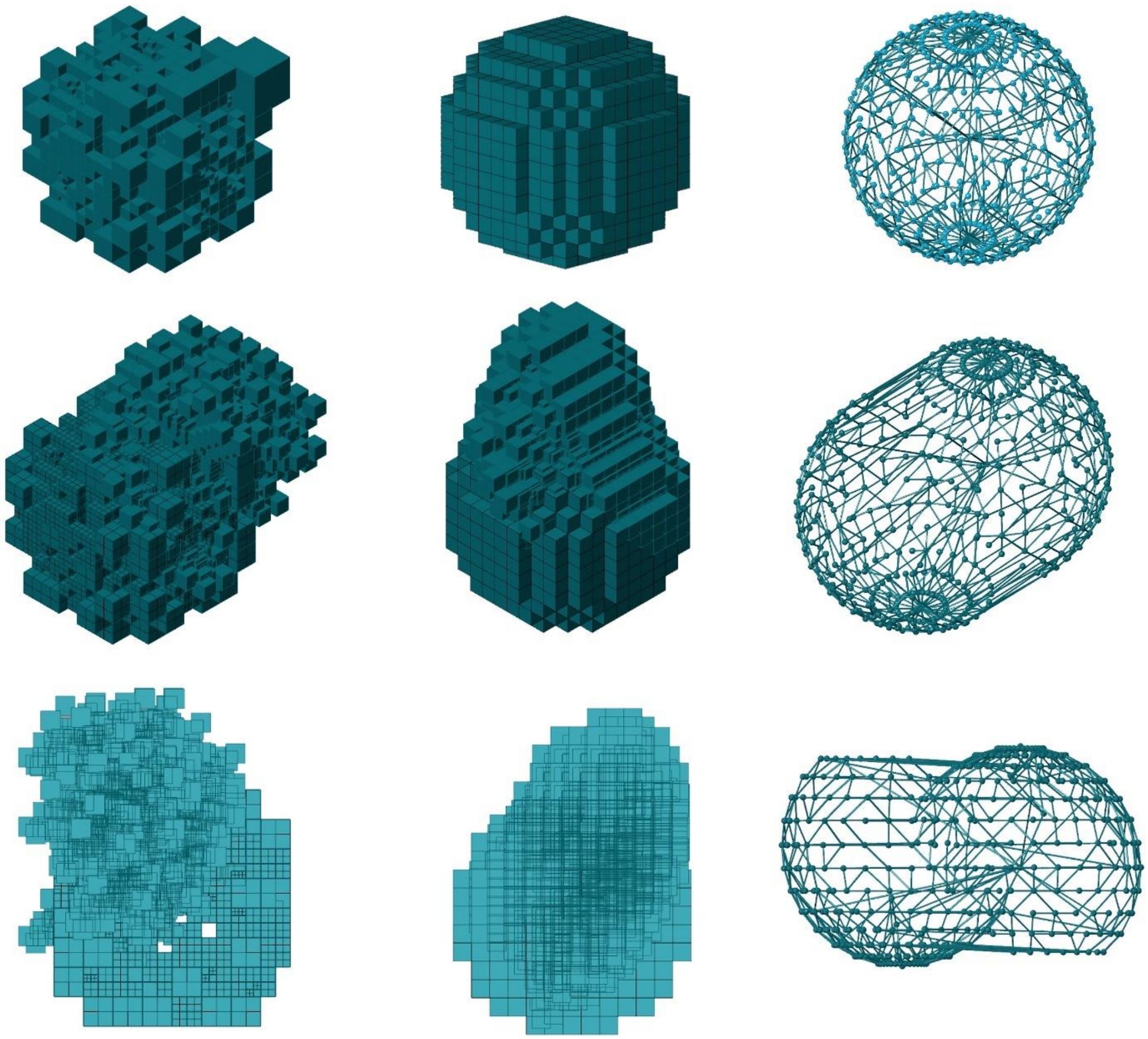


Figure [27]: L – system applied to the nearest voxels/vertex to the attractor.

From top to bottom (the initial state from the same source geometry/ l system applied perspective view/ l system applied side view)

From left to right (Octree/ voxels/ Tetra-Meshes)

4. Conclusion

4.1 Affordances and Results

Voxels and Tetra-Meshes representation had the capacity to reshape the boundary of the initial design schema. Using voxel-based representations (fixed size and octree) shows a stable frame of stacking. It blurs the boundary of the original schema surface. This aggregation of voxels makes it hard to recognize any previous notion of surface and continuity. Such thing sheds the light on using voxels for the importance of organization (stacking) vs the composition as a representation. On the other hand, experiment with Tetra-Meshes are different to other representations of Voxels. In its form, a Tetra-mesh provides XYZ vertex coordinates and the connectivity of vertices allows to maintain the exterior boundary of the schema while breaking the surface rigidity for rule adaptation.

Shape mutation allows for the definition of a design space by using a specific representation. This offers architects a significant amount of control over features, such as stretching or stacking both in Tetra-Meshes and Voxels, namely aspects of design that can be attributed to a specific representation. The high degree of separation between the architect's design schema (initial schema) and the representations means that these design schemas are unanticipated in their behavior and structure, such things might be inspiring towards innovative space of representations while thinking about the larger system.

Using CA and L-system is merely a design methodology the designer is responsible for to specify the design adaptation process. It is important to employ this design methodology to manipulate the representation in an efficient and logical way. In this prototype, CA worked efficiently in voxel's space since it is organized as grid without breaking the structural organization, On the other hand, in the Tetra-Meshes edges were removed in the process resulting in some vertices in space disconnected breaking the structural logic (edges vertices).

On the other hand, L-system was more suitable for the Tetra-Meshes for stretching behavior took place that maintained the general connectivity and structure of edges, however, in the voxel space, it was a mere stacking of more voxels irrelevant to the general structure and original schema.

4.2 Limitations

This experiment was about exploring affordances of Voxels and Tetra-Meshes behavior, such limitations has been addressed in the previous section as behavioral experiment by applying CA and L-system. Such experiments allow to think about the next steps (see section 4.3 and 5.2). However, some limitations can be addressed by considering the possibility to explore the prototype as a design tool/plugin such as:

- Prototype code requires a slider exploring the solution space of each geometry in Tetra Mesh representation for a logical translation. It would be possible to explore different strategies for coding the Tetra-Mesh representations.
- Using Grasshopper interface has advantages in visualizing each step while constructing code in python and using grasshopper components (advantage in debugging). However, it would be better to structure the code in lower level languages such as C and C# for better and efficient performance in translating initial schemas to its representations

To further explore based on these limitations on prototype level:

- Compacting the parametric and python code in grasshopper to allow fine translation of geometry to its representations without using Grasshopper sliders for logical mathematical translation of each geometry (prototype code requires a slider exploring the solution space of each geometry in Tetra Mesh representation).

- Incorporate the tool/plugin created with further design programs such as Autodesk, Maya, AutoCAD, and 3DsMax.
- Allow accessibility to plugin in scripting languages such as Maya Embedded Language (MEL) for feasible computational approach in modeling.

4.3 To Explore

This experience demonstrated that experimental conditions within the representation can amplify the discovery of responses that cannot be predicted from the initial design schemas. Thus:

- It is necessary to explore further with more representations, its relation to the original schema, and its behavioral possibilities. The focus on such behaviors may lead to greater morphological diversity.
- Implementing this strategy on architecture design for a precise embodying of the hypothesis.
- Superimpose the representation in the same space, such approach should allow us to explore their behavior relatively to the others.

4.4 Contributions

- Speculate on a framework for geometry adaptation for architecture morphology, tracing back theoretical background of adaptation in architecture with early implementation and recent work in strategies for form finding.
- A computational approach and generative design method in creating the voxels (fixed dimension and octree) and Tetra Meshes representations from initial geometry
- Code Cellular Automata rules and parametric L-System as a metaphor procedure of architecture design decision for a morphological change in the specified Voxels and Tetra Meshes representations.

5. Discussion

5.1 Architectural Narratives

To raise a question of typology in architecture is to raise a question of nature of the architecture work itself.[16]

Fredric Jameson, when explaining his initial experience of the Bonaventure Hotel in downtown Los Angeles, stated, "*I am proposing the notion that we are here in the presence of something like a mutation in built space itself. My implication is that we ourselves, the human subjects who happen into this new space, have not kept pace with that evolution: there has been a mutation in the object unaccompanied yet by any equivalent mutation in the subject. We do not yet possess the perceptual equipment to match this new hyperspace, as I will call it, in part because our perceptual habits were formed in that older kind of space I have called the space of high modernism… The newer architecture therefore-like other cultural products I have evoked in the proceeding remarks stands as something like an imperative to grow new organs, to expand our sensorium.*"[17]

It would be possible to speculate on architectural systems consisting of multiple representations superimposed in the same space creating a dynamic structure. This structure is able to adapt and allow interrelationships between the design rules defined and its performance. This creates a space for mutation in the built structure by adaptation, and morphological changes through its subsystems (representations) defined by the architect's rules. This allows us to think about the possibility of architecture as dynamic and adaptive structure replacing the design of self-contained and static built architecture.

Moreover, it is possible to think about each representation going under morphological changes by expressing itself through underlying complexities that stem from local inputs of the subsystem – such as Voxels, and Tetra Meshes – to a larger modification being linked and modified within its system

[16] Moneo, Rafael. Oppositions 13. On Typology. 1978.
[17] Jameson, Fredric. Postmodernism or, The Cultural Logic of Late Capitalism. 1991.

(composed of multiple representations). This larger system should trend towards local stabilities, adaptations, and modification across subsets of systems while being contextually aware through local interactions, resulting in an architecture as a *narrative of representations.*

This *architectural narrative* could be managed through predetermined goals across time, location, and content set by the designer allowing morphological changes across time. Creating a narrative relayed through representations allowing architects to develop robust narratives that are inherently interconnected. This might result towards a view of architecture as a dynamic system in its response. The question arises, how these representations can be translated from digital-based rules and simulation processes to the physical world? On a larger definition, how can we blend the edge between the digital interface where these representations and rules are set with the physical world where we can build this narrative?

5.2 Next Steps

To build such *architectural narrative*, it is crucial to think about an analog process as a mediator between the digital interface and the physical, taking into consideration the state of the structure (morphological changes) taking place. This drive the notion to speculate on an analog process as the following:

- A robotic arm as a mediator helps to place and to change the state of the representations. One of the challenges for this approach is the movements required and the space occupied by the robot arm creating theses changes. Can it be part of the narrative?
- The representation’s local input -such as voxels- built as robotic systems able to actuate itself and change its location. This set challenges on the method of representations used in the narrative, as well the motion of actuating within the system.
- Fabrication process. Rather than thinking about it as a definite process of construction; has a start and ending sequence, would it be possible to start speculating on notions of adding and removing materials held within this fabrication process?

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