Growth Structures

Christoph Klemmt
Assistant Professor, University of Cincinnati
Partner, Orproject

Satoru Sugihara
Principal and Founder, ATLV
Faculty, Southern California Institute of Architecture

1 INTRODUCTION

In the fields of architecture, design, and engineering, concepts of biomimicry have been applied to various design problems, such as structural systems, architectural form, or new materials, usually by applying specific isolated geometries from nature to the design field (Benyus 1997; Pawlyn 2011; Panchuk 2006; Barthelat 2007). This research instead attempts to apply one of the general concepts of form generation in nature to the field of design: the creation of form through an iterative incremental development and accumulation of material via processes of growth through cell division (fig. 1).

This development of form for architectural use is based on the computational simulation of behaviors and arrangements of small units of material. The units can be simulated to behave similarly to the cells which make up living organisms, or their behavior can follow material, geometric, or mathematical logics.

The aim of developing forms through an iterative growth process is, similar to nature, to continually evaluate and influence the geometry during its formation according to given internal and external influences (Kwinter 2008). In this way, the system can be universally responsive without being bound by the preconceived conditions which need to be set out in a parametric relational model (Leach 1999; Liaropoulos-Legendre 2003).

The cells are calculated iteratively by their center points and can reconfigure in space while attempting to keep a specified distance toward their neighboring cells. This results in larger accumulations of adjacent cells. Two types of topologies have been investigated.

In a static manifold topology, all cells are arranged similarly to the vertices of a mesh geometry. The cell neighborhood, which defines which cells are regarded as neighbors, can be described by the edges of the mesh geometry. It does not change between the iterations of the simulation unless a cell divides, in which case the new cell is inserted into the accumulation.

In a dynamic topology, the cells can freely rearrange, and the neighborhood of a cell is reestablished in every iteration. This may lead to non-manifold or volumetric accumulations of cells.

The two types of simulations have been tested with the design of two permanent installations in the office of an

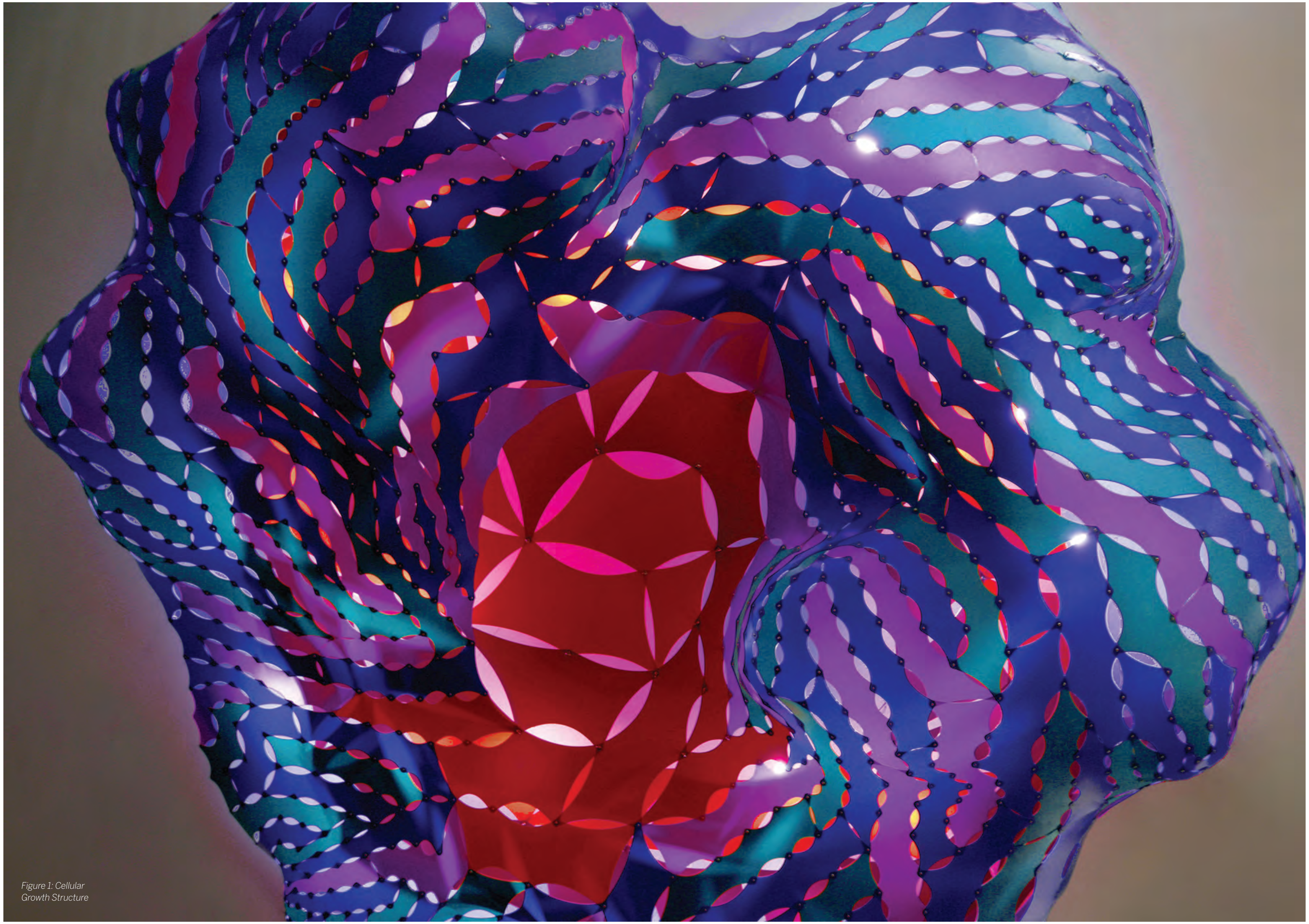


Figure 1: Cellular Growth Structure

IT company. The installations form atmospheric lighting structures underneath the ceilings. The algorithms could be successfully applied to grow geometries which are functional in creating an immersive light environment.

2 RELATED WORK

Simulations similar to the ones proposed in this paper have been developed by artists and designers. The main aim of the simulations is to generate morphologies which can become artworks as final objects, or to use the development of the form as an animation.

George Hart developed a system based on a manifold mesh arrangement of cells. The cells have a spring force between them which keeps neighboring cells at a defined distance from each other. Certain cells are bud cells, which are able to divide. When a cell divides, a new cell is inserted into the mesh and the dividing cell's neighbors are split between the dividing cell and the new cell (Hart 2009).

Andy Lomas uses a similar system to that of Hart, based on a manifold mesh arrangement of cells. Cells, as in Hart's model, have spring forces acting between them, and are, in many of his simulations, also pulled toward a central sphere. Cells which are not direct neighbors are repelled from each other. Cell division in Lomas's simulations is based on a nutrient distribution: cells with a high enough nutrient level will proliferate (Lomas 2014).

Neri Oxman, Christoph Bader, and Dominik Kolb presented the artwork series *Wanderers*, which are described as being developed through growth. To date no scientific paper has been published explaining the generation of the works (Stinton 2014; Domus 2014).

Nervous System used an algorithm similar to that of Oxman, Bader, and Kolb for the design of their Florascene collection (Louis-Rosenberg 2015).

3 ALGORITHM

3.1 Basic Algorithm

The simulations are calculated as particle systems; every cell is calculated by its center point in 3d space. The simulations start with an initial set of cells, which is given.

The new positions of the moving cells are defined iteratively through an acceleration-velocity calculation: In every iteration, the forces which are acting on the cells are added to the velocity of the cell, and then the new velocity is added to the position of the cell. In this model, all cells are calculated as having the same mass.

3.2 Cellular Forces

3.2.1 Neighbor Force

The main forces acting on a cell are forces toward its neighbors. An intended target distance between cells is given, which equals the cell's diameter. If the cells are

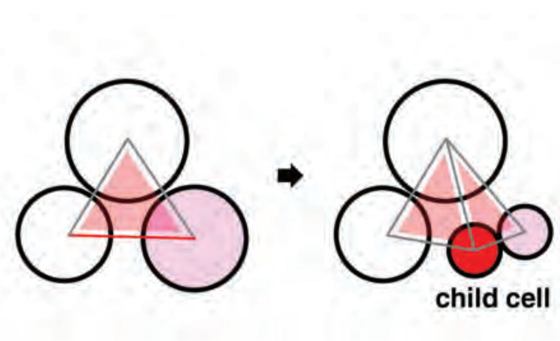


Figure 2: Cell Insertion into Naked Edge

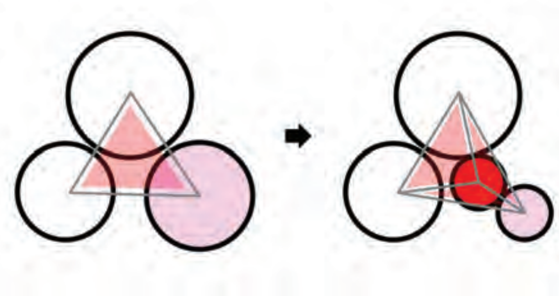


Figure 3: Cell Insertion into Face

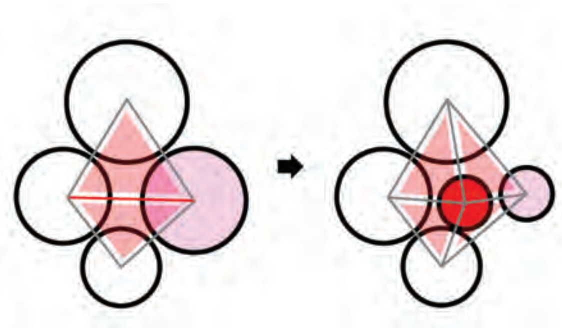


Figure 4: Cell Insertion into Interior Edge

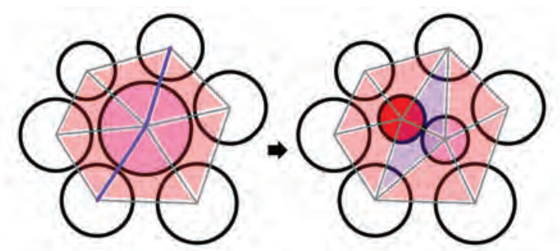


Figure 5: Cell Insertion at Two Connected Edges

closer than this distance, they are pushed apart; if they are further, they are pulled together. The force can act as a spring force with the target distance as the rest length of the spring if the strength is set in relation to the difference from the target distance. This causes the cells to attempt to arrange in evenly spaced accumulations.

The distance of the spring force can be seen as the summation of the size of two cells connected by the spring. The size of a cell can increase through time to simulate growth of cells in size. The size growth behavior influences geometric formation of cells by differentiating distance and density depending on the age of cells.

3.2.2 Repulsion Forces in Middle-Range Neighbors

In addition to the repulsion forces caused by the spring when cells are too close, there is an additional repulsion force which reaches neighbors whose distance is longer than the distance of the spring force. To calculate the repulsion force, firstly the center point of middle-range neighbors is calculated, and the repulsion force from the center point to the cells position is generated. This repulsion force has a tendency to generate coral-like hyperbolic surface formations because when cells are surrounded by other cells, as in a surface, this repulsion force tends to push toward the positive or negative normal direction.

3.2.3 Forces Toward External Objects

The forces and behaviors which are acting on the cells can have external influences. Other geometric objects or attractors in the simulation can have an influence on the cells, or the intercellular forces and behaviors can vary depending on the position of a cell in space.

3.2.4 Planarity Force

Cells can be programmed to attempt to form locally planar arrangements. A normal direction of the cells and its neighbors is established, and the cell is pulled along the normal, toward the center point of its neighbors.

3.2.5 Strata Force

A strata force controls the formation of parallel strata of cells. The direction of the strata is given by their normal vector. The cells are pulled along this normal vector toward the center point of their surrounding neighbors.

3.3 Topology

3.3.1 Static Manifold Topology: Formation of Cells as Polygon Mesh with Edges and Faces

Neighbors of a cell are established in the initial state or at the moment of cell division, and do not change until the next cell division. The spring force is applied only to the established static neighbors.

In this topology, cells also form a polygon mesh. Each cell becomes a vertex of a polygon mesh, and edges run from a cell to neighbor cells. Each cell also keeps

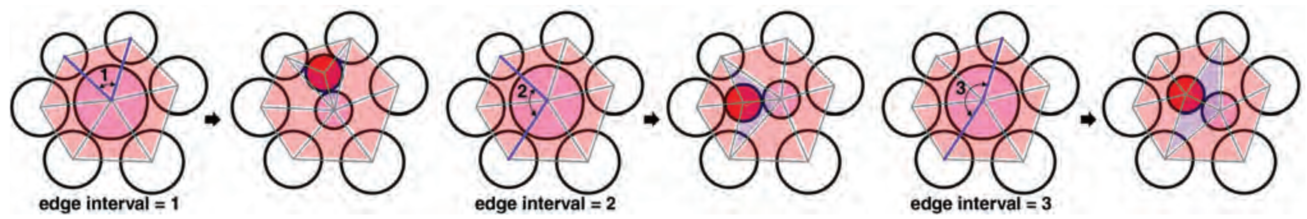


Figure 6: Cell Insertion at Connected Edges with Different Intervals of Separation

information of its polygon mesh faces. A face consists of three cells, which are all connected as neighbors. Vertices, edges, and faces in a polygon mesh are updated every time when cell division happens.

The static topology is suitable to generate manifold surface structures because new cells, edges, and faces are inserted, maintaining the local topological condition of manifold surfaces. It is also suitable to have inner cell divisions with denser cells and smaller subdivided mesh faces because the neighborhood relationship is not based on distance of cells but on established connections.

3.3.2 Dynamic Topology

The neighborhood of the cells is dynamic and is reevaluated at every iteration. The cells which are regarded as neighbors are defined by their distance and by a minimum and maximum count of neighbors of a cell. In this system, the topology of the accumulation can change and evolve over time.

It was found that for the dynamic topology simulations, a marginal growth of the system is more successful, as a growth on the inside requires the whole system to expand in order for the inner cells to keep their intended target distance. This can easily lead to overly dense areas on the inside.

3.4 Cell Proliferation

Cells can divide, in which case a new cell is inserted into the accumulation. The new cell can be inserted closely to the parent cell, or it can be inserted centrally between a few of the existing cells.

3.4.1 Division Triggers

Different triggers for the division of the cells have been investigated:

- Cells divide if they are positioned on the outside of the accumulation.
- Cells can only divide after a certain count of iterations, which makes the youngest cells always divide.
- Cells divide if their size grows more than a specified size.
- Cells divide randomly.
- Cells divide only if the number of neighbors (edges) are less than a certain number.
- Only cells which are activated in the beginning divide.

3.4.2 Insertion of a Cell into a Naked Edge

When a cell remembers neighbors as edges, a divided child cell can be inserted in the middle of one of the naked edges (fig. 2). The original naked edge and the triangular face are removed, and two new faces and three new edges are added.

3.4.3 Insertion of a Cell into a Face

A new child cell can be inserted into a face as well as an edge. When a child cell is inserted on an existing face (fig. 3), the face is replaced with three new faces with three new edges. The edge count on the parent cell is increased by one.

3.4.4 Insertion of a Cell into an Interior Edge

Another type of cell insertion is to add a new child cell on an interior edge which has two faces, on both sides of the edge (fig. 4). In this case, the interior edge is removed, and the two existing faces are replaced by four new faces and four new edges.

3.4.5 Insertion of a Cell at Two Connected Edges

One more type of cell insertion is to pick two edges that are separated by three or more faces, duplicate the two edges, and insert two new faces between each of the new and the existing edges (fig. 5). In the case of Figure 5, two edges and three faces are replaced by five new faces and five new edges.

When the two edges picked are just two faces apart, this insertion becomes equivalent to the insertion into an interior edge, which was described in section 3.4.4. If the edges are one face apart, the insertion is equivalent to the insertion into a face described in section 3.4.3 (fig. 6).

When looking at the changes of edge count on a cell after cell division and insertion, the edge counts of parent cells and neighbor cells increase most of the time by adding new edges. However, with the cell insertion at two connected edges separated by three or more faces, the edge count decreases by one. Figure 6 shows that when the edge interval is three, the edge count of the parent cells is six before division and becomes five after division. When a polygon mesh geometry generated by the cell division should be clean, without too many edges, this characteristic is important and this insertion method works effectively.

Figure 7: Cell Growth with Division on Naked Edges

Figure 8: Cell Growth with Division on Faces

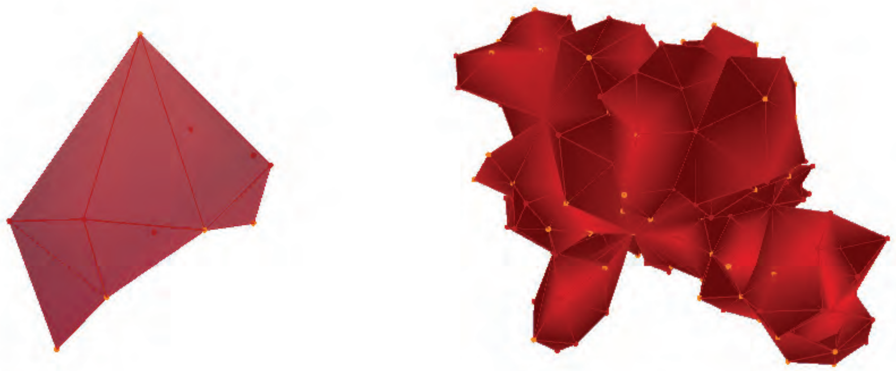


Figure 9: Cell Growth with Division on Interior Edges

Figure 10: Cell Growth with Division at Two Connected Edges

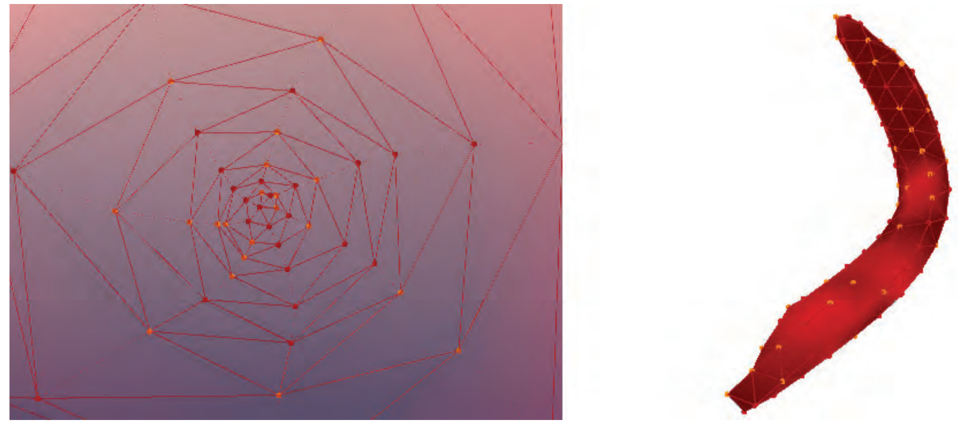


Figure 11: Cell Growth with Edge Count Limit

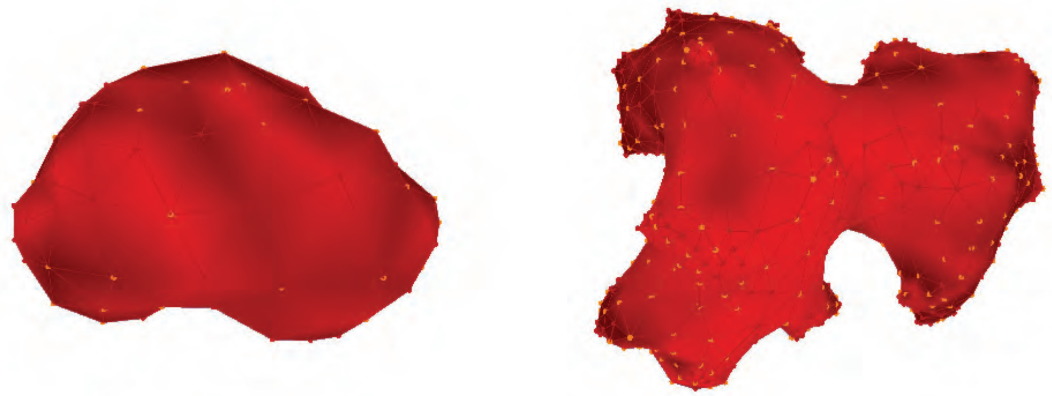


Figure 12: Cell Growth with Edge Count Limit and Probabilistic Exception

4 GENERATED GEOMETRIES

The cell division algorithms described in section 3 (with variation of insertion behaviors and division triggers) generate different geometric results. This section describes characteristics and geometric qualities of results generated by the cell division algorithms with different settings.

4.1 Static Manifold Topology

4.1.1 Cell Division on Naked Edges

When the cell division with insertion on naked edges is applied to a single triangular mesh, it grows into a longer mesh strip because it only adds more naked edges without any interior edge developed (fig. 7). When division is triggered randomly, it tends to make the strip wrinkle because some cells get more edges as a result of the division.

4.1.2 Cell Division on Faces

When the cell division with insertion on faces is applied to a tetrahedron mesh, it generates a closed polygon mesh because the face insertion maintains the closed mesh topology (fig. 8). It also tends to make the mesh spiky because triangles are constantly added inside existing triangles, and the edge count of older cells increases.

4.1.3 Cell Division on Interior Edges

When the cell division with insertion on interior edges is applied to a tetrahedron mesh, it tends to make the polygon mesh less spiky than face insertion. The resultant geometry is nevertheless bulky because it does not generate sharp triangular geometry as face insertion does, but it still increases the edge counts on older cells (fig. 9).

4.1.4 Cell Division at Two Connected Edges

When the cell division with insertion at two connected edges is applied to a tetrahedron mesh, it tends to make the mesh smoother than previous types of insertion because it can decrease the edge count on dividing parent cells, avoiding a vertex with too many edges (fig. 10).

4.1.5 Smoother Cell Division with Edge Count Limit

When the cell division with insertion at two connected edges has another division control limiting the division if the edge count of a cell is above a certain number, and it is applied to a tetrahedron mesh, it generates a cleaner closed polygon mesh (fig. 11). In the figure, the maximum edge count is six. However, this limitation is strong, and it either generates very regular growth or stops growth entirely once the edge counts of all cells has reached the limit.

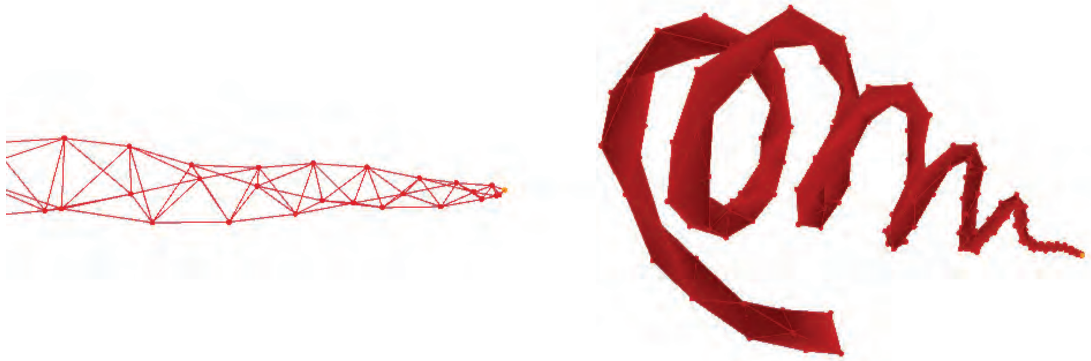


Figure 13: Cell Growth with Cascading Division Control

Figure 14: Cell Growth Branching with Single Active Cell

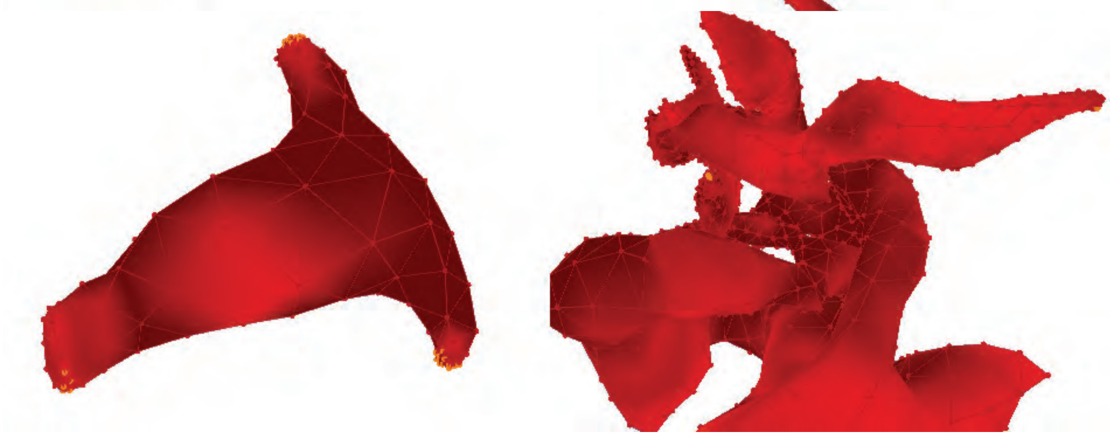


Figure 15: Cell Growth Branching with Cluster of Active Cells

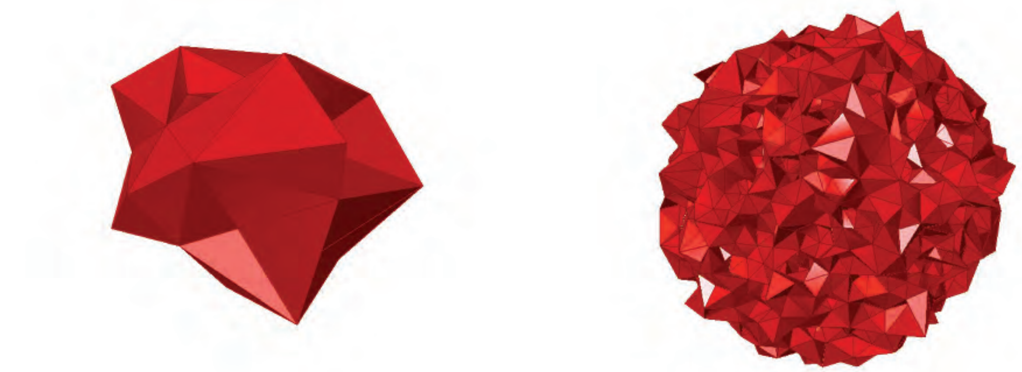


Figure 16: Cell Division with Neighbor Force

Figure 17: Cell Division with Local Planarity Force

Figure 18: Cell Division with Unary Gravity Force and Base Plane.

When the algorithm allows division in a certain probability, even after the edge count reaches the limit, it can ease the strict characteristic of the edge count limitation and can generate a smoother closed polygon mesh more effectively (fig. 12). In the figure, the maximum edge count is six, but the division is allowed if it creates the seventh edge with 20 percent probability.

4.1.6 Branching with Cascading Division Control

When cell division is controlled by a Boolean flag to allow division (active) or not (inactive) and a dividing parent cell activates a child cell and inactivates itself right after dividing once, the cell division happens in a cascading manner (fig. 13).

4.1.7 Branching with Single Active Cell

If cell division is controlled by a Boolean flag and a dividing parent cell sets a child cell as perpetually active and sets itself inactive most of time (if a parent allows itself to stay active probabilistically instead of setting itself inactive), then the algorithm generates a branching structure as polygon mesh. A parent cell which stays active divides one more time and create another series of cascading active cells (fig. 14).

4.1.8 Branching with Cluster of Active Cells

When the algorithm allows all cells to stay active at the moment of cell division as far as it satisfies the edge count limitation with probabilistic exception, it also generates a branching structure as polygon mesh (fig. 15). Older cells become inactive because they reach the limit of edge count, but clusters of younger cells keep growing wider tubular mesh geometry. When the probabilistic exception allows extra cell division, it tends to branch out into another tubular geometry.

4.2 Dynamic Topology

4.2.1 Cell Division with Neighbor Force

When the cell division operates with each cell reacting to neighbors at a target distance, it tends to form blob-like volumetric solids (fig. 16). If the neighbor reaction force is set to behave as a spring, the cells approach an even spacing throughout the accumulation.

4.2.2 Planarity Force

When the cell division operates with a planarization force, cells tend to form localized planar arrangements. As the quantity of cells increases, multiple planarized conditions tend to form within the geometry (fig. 17).

4.2.3 Gravity and Base Plane

When the cell division operates adjacent to a ground plane and with a unary gravity (z-axis) force acting upon the cells, growth tends to flow along the ground surface. Depending on the strength of the unary force, these

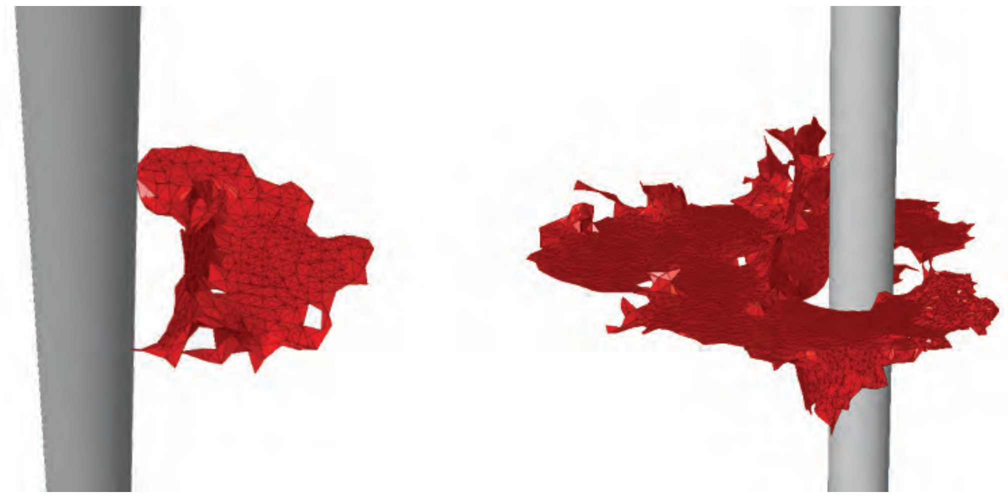


Figure 19: Cell Division with External Object Force

Figure 20: Cell Division with Stratification Force

meshes can form planar surfaces along the ground plane as growth continues (fig. 18).

4.2.4 Object Force

The cell division can be set to operate in the presence of an external object with prescribed forces. In these cases, cells can be drawn to, repelled away from, or prompted to grow around existing geometries (fig. 19).

4.2.5 Strata Force

When the cell division with a strata force is applied, cells tend to grow in multiple parallel layers. This growth operates in a manner similar to the planarization force, though all strata of cells have the same normal vector (fig. 20).

5 APPLICATION AS LIGHT INSTALLATIONS

The cellular growth simulations as described above have been tested for their architectural potential with the construction of two light installations. Both installations have been designed and manufactured for the offices of an IT company in Beijing.

5.1 *Naizoshoku*: Static Manifold Topology

5.1.1 Site and Requirements

Naizoshoku is a ceiling installation located above the seating area in the cafeteria space in the office. The installation is made out of translucent polymer panels hung from the ceiling with suspension wires which diffuse the ceiling lights above the installation. The geometry of the installation is generated though the cell division algorithm, pursuing an expressive complexity and atmospheric light diffusion effect by exploring different settings and behaviors of the algorithm.

5.1.2 Design of Initial Geometric Condition

The cell division algorithm with static manifold topology can start with a given polygon mesh by converting all vertices into initial cells and edges into initial neighborhood spring connections. The initial polygon mesh is carefully designed to indirectly control the outcome of the algorithm to achieve a certain topological and geometric complexity (fig. 21).

5.1.3 Division Control by Location

The cell division algorithm for *Naizoshoku* uses insertion at two connected edges and edge count limitation with probabilistic exception. Cell division is invoked randomly, but it adds extra division control by z coordinate of cell positions. When cells are in the lower z coordinate position, the probability to invoke cell division is higher, and in the higher z coordinate position, the probability is lower. This is to differentiate cell density depending on height, and to generate finer and denser geometry toward the bottom and rougher and sparse geometry at the top (fig. 22).

5.1.4 Formal and Structural Optimization by Physics Simulation with Gravity

After the cell division algorithm generates the result as a polygon mesh, the structural ability of the geometry is examined by a physics simulation. In the simulation, vertices are converted into particles, edges are converted into compressive connections, hanging suspension wires are added from the ceiling plane to some selected vertices, and then gravity is applied to the particles (fig. 23). When the simulation runs, it shows the deformation of the mesh under the forces, and it also visualizes the geometric deviation between the original and the deformed. This informs us if the locations of suspension wires work effectively, and this iterative feedback information was used to find a feasible and effective layout of the wires.

5.1.5 Strip Panelization and Colorization

The polygon mesh structurally optimized with the physics simulation was then panelized into strip panels (fig. 24). This panelization method was developed by Marc Fornes in his installations (Fornes 2014) and has benefits of minimizing the number of panels and joints while also giving a design opportunity to express a certain grain texture. The generated strips are colorized based on the average area of a triangle in a strip to have a gradient color transition from the top toward the bottom. The number of colors is limited to five for material and cost efficiency. Then the strip panels are unfolded with joint holes and labels to be fabricated by laser cutting (fig. 25).

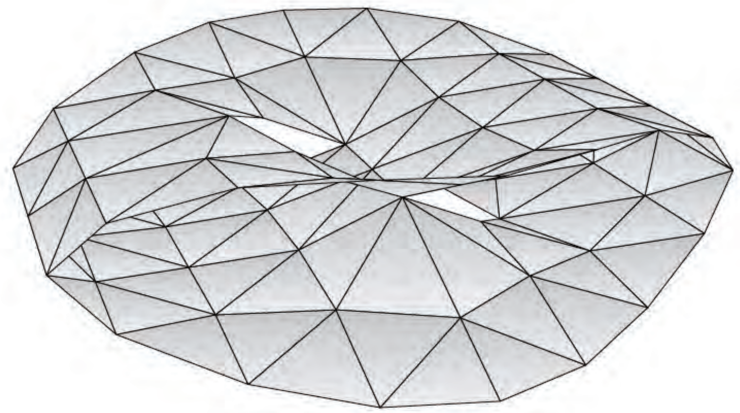


Figure 21: Initial Mesh Geometry for Naizoshoku

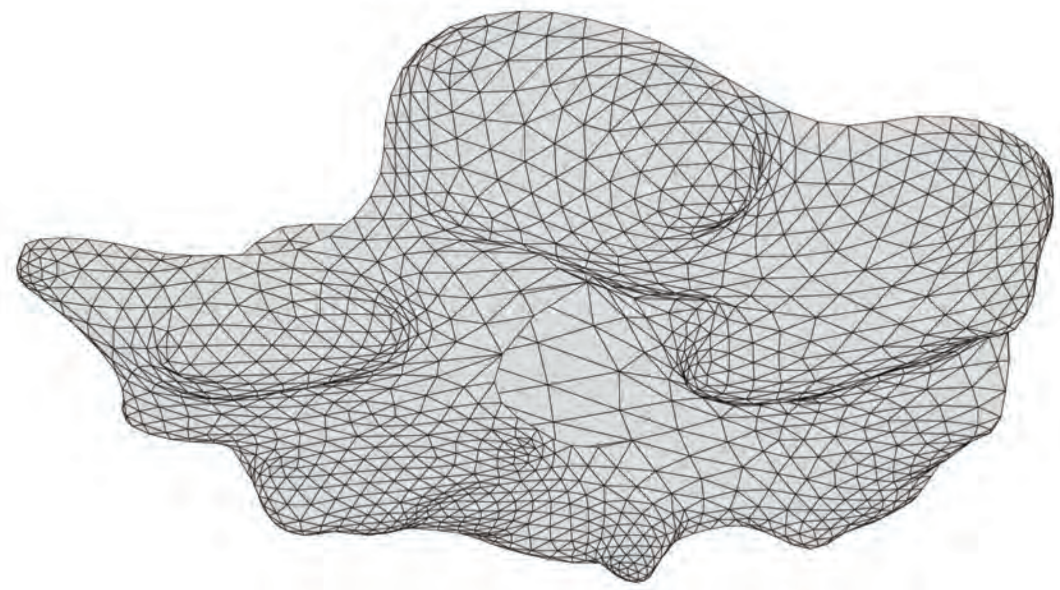


Figure 22: Cell Division and Growth Result

Figure 23: Physics Simulation with Tension and Gravity

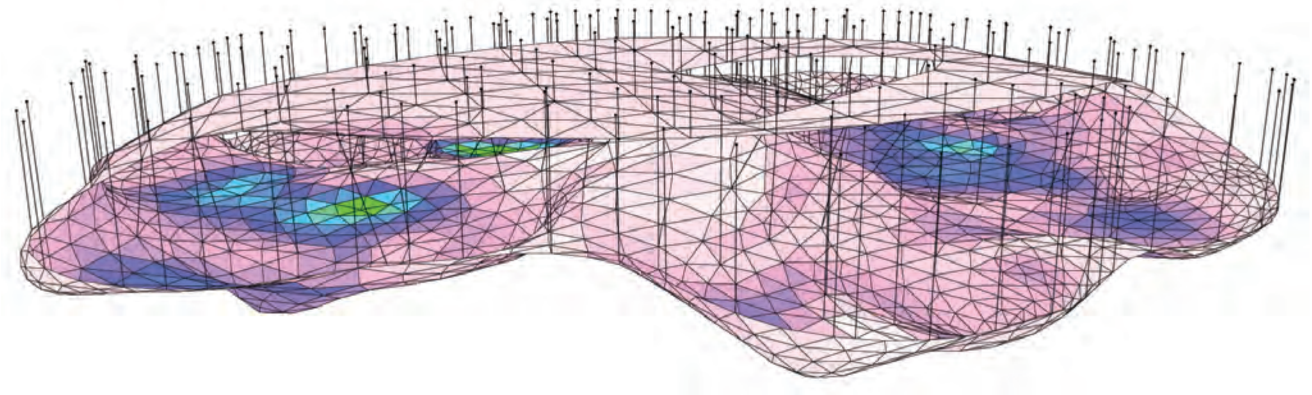
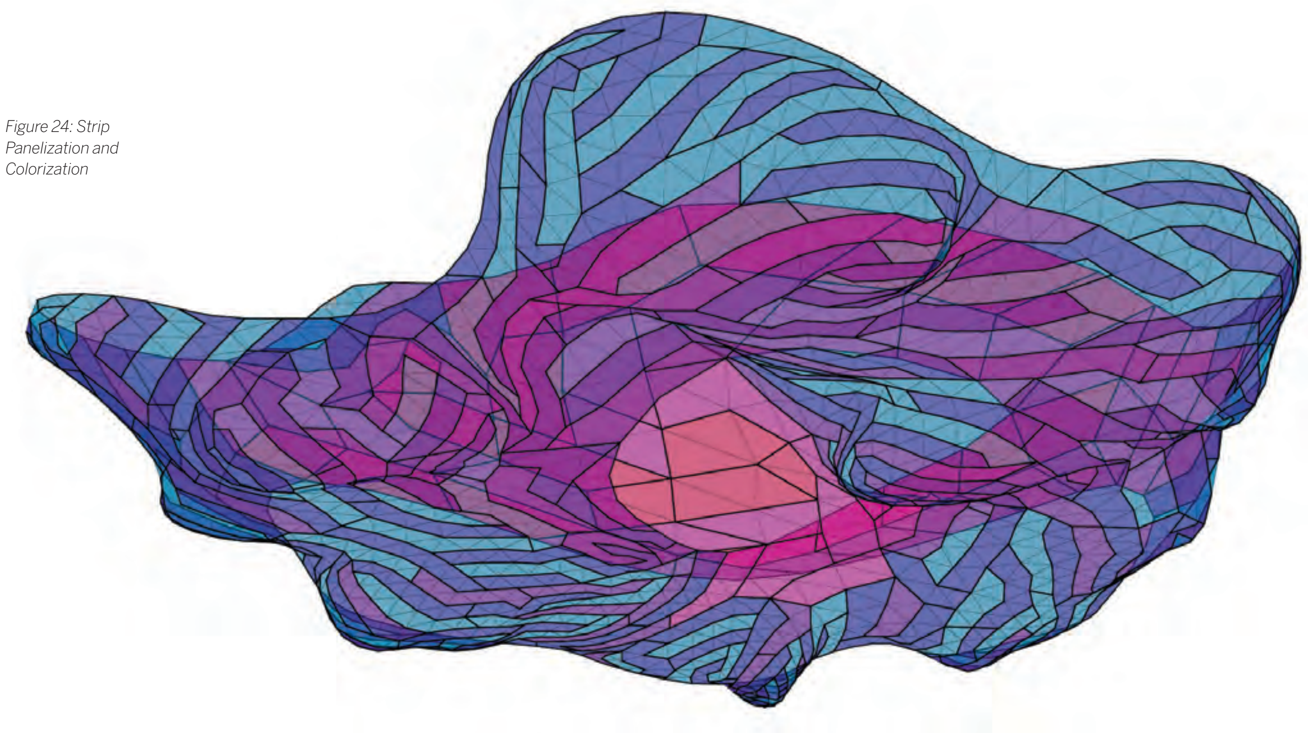


Figure 24: Strip Panelization and Colorization



5.2 Gaizoshoku: Dynamic Topology

5.2.1 Site and Requirements

Gaizoshoku is positioned in the lobby of the office. Apart from being a light installation, it also serves various other functions, such as integrating a reception desk and framing the company logo. Specific requirements concern the human circulation and accessibilities around the installation.

The geometry of the installation therefore had to develop in a way as to cover the ceiling at the highest level while being confined to a closer area in plan at a height where it can be touched. On the lower level, it needed to form the front and top of the reception desk.

5.2.2 Settings of the Algorithm

The growth algorithm used is of the dynamic topology; cells can rearrange freely. Cell proliferation occurs marginally. Cells for division are identified by having less than three neighbors within 1.2 times the target distance.

A planarity force is applied. The initial cells are placed at the bottom of the space, and a reverse gravity force causes the cells to slowly grow upward.

A strata force is applied to the cells in order to generate layers of cells parallel to the ground plane. The intensity of the strata force increases toward the top. This results in the cells at the bottom having a minimal horizontal orientation while the upper cells have a strong horizontal orientation.

An object force is applied which pulls cells toward a central cylinder. This object force decreases from the bottom toward the top and keeps the lower cells closer together while the upper cells spread out further. A secondary object force is used to keep the lowest cells within a geometry suitable for the reception desk.

5.2.3 Panelization and Colorization

Panels are based on a triangulation between neighboring cells. The panel geometry allows for an overlap of adjacent panels with two fixtures along shared edges, in order to avoid a possible rotation around a single fixture.

The panel geometry has a gradient of openness which was used to control the lighting. Direct light is allowed through above the reception desk, while in the less used areas, the light is filtered by the closed panels.

The surface curvature has been used for the colorization, which makes the higher-level marginal panels darker while the central panels are red.

The locations of suspension wires are determined through iterations, with the physical simulation as described in section 5.1.4 (fig. 26).

5.3 Construction

Both installations were manufactured from custom-colored Polypropylene sheets. The material was cut and connected by bolts. The installations were then hung from the ceilings, while the front and top of the reception desk was attached to a steel frame (figs. 27–29).

6 CONCLUSIONS AND FUTURE WORK

The two installations are successful applications of the cellular growth algorithm. In both cases, different settings of the algorithm have been applied to specific design scenarios, and although the growth behavior is highly emergent, it was possible to guide the development of the growth to meet relatively basic, though specific, functional and spatial requirements.

Those requirements have not been met through 3D modelling nor through the set-up of a relational model, but solely through their interpretation into intercellular behaviors, external forces, and proliferation characteristics. From this set of rules, the algorithm was able to mediate the cellular matter over time into a geometric formation suitable to fulfil the given demands.

The application as light installations allowed the authors to test a basic functional performance for a design brief that allowed a large degree of freedom. It is anticipated that further refinement and control of the development of specific geometric traits and outcomes can make the cellular growth simulations applicable to more complex architectural problems such as space planning, structural requirements, and environmental performance. Due to the universal applicability of the manipulation of small units of material, cellular growth simulations have shown to be a promising tool for functional algorithmic design.

REFERENCES

Barthelat, Francois. 2007. "Biomimetics for next generation materials." *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences* 365 (1861): 2907–19.

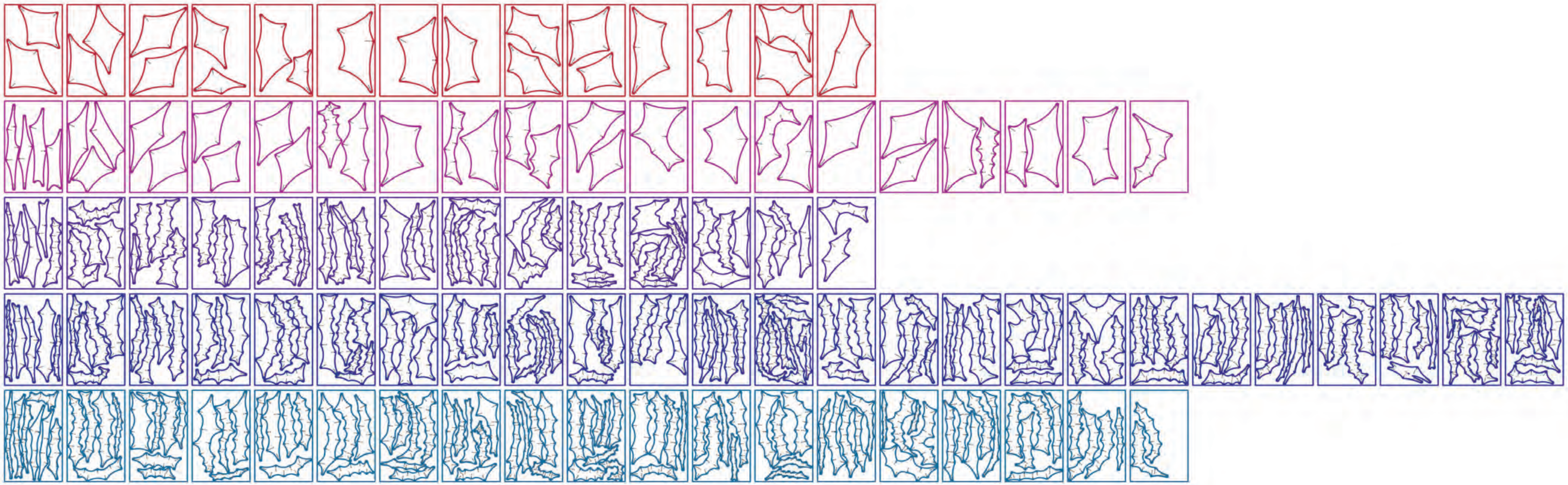
Benyus, Janine M. 1997. *Biomimicry: Innovation Inspired by Nature*. 1st Edition. New York: William Morrow.

Domus. 2014. "A dress for the Moon." December 6, 2014. https://www.domusweb.it/en/news/2014/12/16/neri_oxman_wanderers.html.

Fornes, M. 2014. "Nonlin/Lin Pavilion." In *Paradigms in Computing*, edited by David Jason Gerber and Mariana Ibañez. Los Angeles: eVolo Press. 184–89.

Hart George. 2009. "Growth Forms." *Proceedings of Bridges*. http://georgehart.com/Growth/GrowthForms.pdf

Figure 25: Unfolded Strip Panels



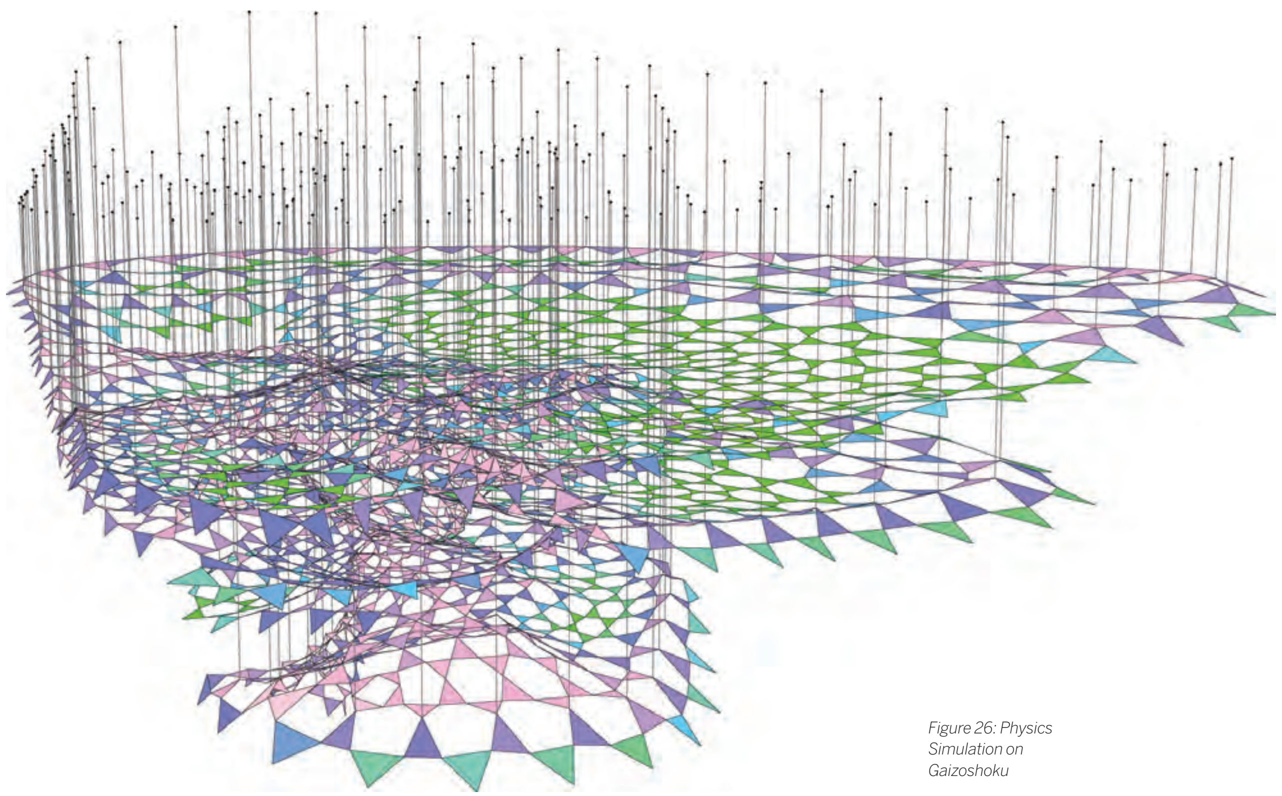


Figure 26: Physics Simulation on Gaizoshoku

Kwinter, Sanford. 2008. *Far From Equilibrium: Essays on Technology and Design Culture*. Barcelona: Actar.

Leach, Neil. 1999. "Digital Morphogenesis: A New Paradigmatic Shift in Architecture." *Architectural Design* 79. London: Wiley.

Liaropoulos-Legendre George. 2003. *Ijp: The Book of Surfaces*. London: The Architectural Association.

Lomas Andy. 2014. "Cellular forms: an artistic exploration of morphogenesis." In *ACM SIGGRAPH 2014 Studio*. New York: ACM.

Louis-Rosenberg, J. 2015. "Floraform – An Exploration Of Differential Growth." *Nervous System Blog*, June 22, 2015. http://n-e-r-v-o-u-s.com/blog/?p=6721.

Panchuk, Neal. 2006. "An Exploration into Biomimicry and its Application in Digital & Parametric Architectural Design." MSc Thesis, University of Waterloo.

Pawlyn, Michael. 2011. *Biomimicry in Architecture*. London: Riba Publishing.

Stinton Liz. 2014. "Wild Biomorphic Spacesuits Designed to Survive Hostile Planets." http://www.wired.com.

PROJECT CREDITS

Title: Naizoshoku Gaizoshoku
Architects: Orproject & ATLV
Client: Baishan Cloud
Interior LDI: Pinshang Design
Project Architects: Christoph Klemmt, Rajat Sodhi, and Satoru Sugihara
Project Manager: Shuai Yang
Project Team: Sambit Samant
Photography: Jiao Yang, Orproject

ACKNOWLEDGEMENTS

The project has been developed in close collaboration with Rajat Sodhi.