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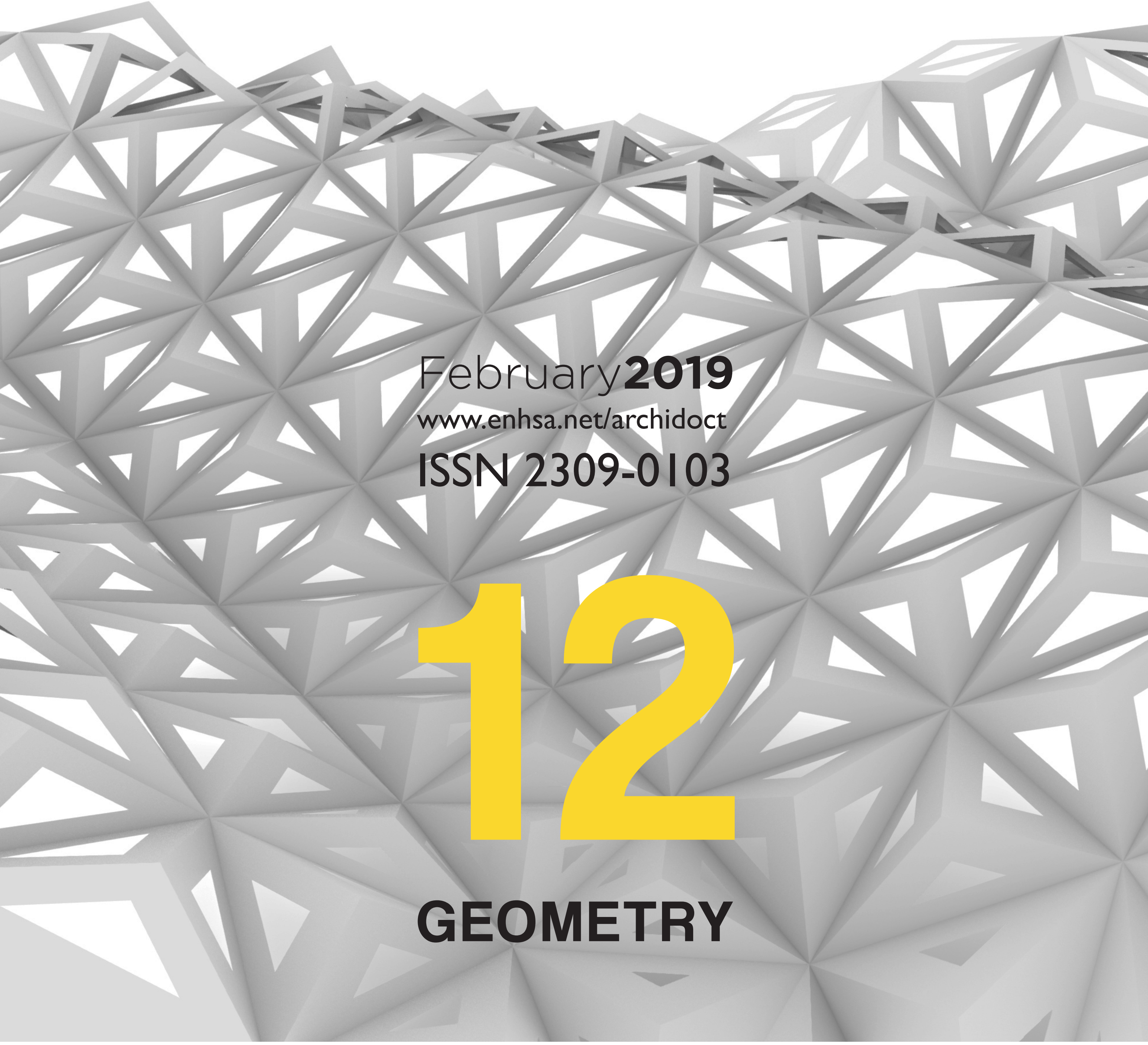

February**2019**

www.enhsa.net/archidoct

ISSN 2309-0103

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ISSN 2309-0103
www.enhsa.net/archidoct
Vol. 6 (2) / February 2019

Cellular Design

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Abstract

Architectural designers have had a long interest in self-organizing principles and designers have applied emerging systems to a wide variety of projects. Often, components of a project or relationships between components are defined by the designer while the emerging system reacts to those, or self-organizing geometries are made to suit a given site and program. This research instead attempts to build a self-organizing system from the bottom up, so that all parts of the material accumulation are developed through local system interactions only. We therefore propose the use of simulations of intercellular behaviors as an architectural computational design tool. Small units of material, the cells, are programmed to arrange themselves according to intercellular as well as external behaviors. The intercellular logics can be geometric or mathematical rules, or they can attempt to simulate natural systems such as the cellular behaviors and growth in organisms. Different types of cellular simulations have been programmed. A set of behaviors has been developed in order to generate a variety of morphological traits for potential applications in architectural design. The generated geometries portray various characteristics of architectural relevance, generated through the emergent intercellular behaviors as well as external influences. The simulations have been tested with the design of two case studies: A permanent installation in an office, and the design of a house. While the simulations require significant improvements in order to become more effective as design tools, they have generated promising designs for the case studies.

Keywords

architecture; structure; cell division; cell proliferation; intercellular behavior; developmental biology; growth

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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 by cell division. (Figure 1)

Falling within the realms of both Generative Design (Shea et al. 2005) as well as Artificial Life (Langton 1998), computational simulations are used for the creation of those processes. Whereas in Artificial Life a main focus is on the study of life processes, this research specifically aims at the generation and control of the resulting geometry. This development of form for architectural use is based on the simulation of behaviors and arrangements of small units of material. The units can be simulated to behave similarly to the cells that make up living organisms, or their behavior can follow material, geometric or mathematical logics.

Architectural designers have been interested in self-organizing systems for several years and have applied emerging geometries to various projects. However, usually components and their relationships are predefined, the self-organization is limited to react to given geometries, or emerging geometries are made to fit a given site and program. Instead, the aim of developing forms through an iterative growth process is, similar to nature, to continually evaluate and influence the geometry during its formation, so that the final form is solely generated through a bottom-up system of local material interactions (Kwinter 2008). In this way, the system can be universally responsive without being bound by the preconceived conditions that 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 3d space while attempting to keep a specified distance towards their neighboring cells. This results in larger accumulations of adjacent cells. Growth and decay processes can be simulated by triggering the addition or removal of cells. Cells can be differentiated by the assignment of specific behaviors or functions. The work in this paper is a generalization of the existing algorithms as presented in section 'Related work'. The simulations in this paper allow the cells to continually change their cell neighborhood based on their movement. Also they allow for volumetric cell accumulations with a thickness of several cells, rather than accumulations of only linear or single layer surface formations as in previous work. Different typologies of the cell accumulations were investigated, and different intercellular behaviors and external influences were tested, with the aim of generating a variety of morphologies that can become useful for architectural design.

2 Related work

Similar simulations to the ones proposed in this paper have been developed by artists and designers as well as by scientists. In art and design, the main aim of the simulations is to generate morphologies, which can become artworks as final objects or which can be used as animations. In science, the aim of the simulations is to gain new knowledge and understanding of biologic processes.
Early simulations such as cellular automata (Wolfram 1983), the Game of Life (Gardner 1970)

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or diffusion limited aggregation (Witten and Sander 1981) all use small units of material as their basis, the voxels or solid cells, similar to the proposed simulations of this paper. However, in those simulations the voxels are usually positioned in regular lattice arrangements such as orthogonal equidistant grids.

2.1 Cellular growth simulations in art and design

George Hart developed a system based on a manifold mesh arrangement of cells, with only specific bud-cells allowed to divide (Hart 2009), generating tubular and branching structures with this algorithm. Andy Lomas uses a similar system based on a manifold mesh arrangement of cells, with cell division based on a nutrient distribution (Lomas 2014). Lomas uses significantly larger numbers of cells than Hart. Surface behaviors emerge as the cell layer expands and starts to fold. Neri Oxman, Christoph Bader and Dominik Kolb presented the artwork series Wanderers, described as being developed through growth (Patrick 2015). Based on the visualizations, it is assumed that linear and manifold surface based simulations have been used similar to those presented in this paper, with cells pulled towards external geometries. Alisa Andrasek developed architectural geometry using manifold surface based simulations at the Bartlett University College London (Andrasek 2016).

2.1 Cellular growth simulations in science

In developmental biology, assumptions on the development of organisms on a cellular level are tested through computational simulations (Merks and Glazier 2005, Palm and Merks 2014). Those are applied to various processes such as embryonic growth (Wolpert et al. 1998), plant development (Merks et al 2010), the development of marine life (Kaandorp et al. 2005, Kaandorp and Kübler 2001), or at the level of cells and molecules (Merks and Glazier 2005). The study of the processes using computational simulations allow for a research at a precision that would otherwise not be possible (Walpole et al. 2013). In cancer research, the growth of tumors is simulated computationally in order to understand the precise mechanisms that lead to its development and to the adverse proliferation of the cells (Shirinifard et al. 2009, Milde 2013, Jiao and Torquato 2012, Gevertz and Torquato 2009, Bearer et al. 2009, Neufeld et al. 2013).

3 Simulation Typologies

During the setup of the simulations, some of the major behaviors are defined that allow for a classification of the growth simulations according to these characteristics:

3.1 Cellular neighborhood

The set of surrounding cells that a cell regards as its neighbors shall be referred to as the cell neighborhood. In a simulation with static cell neighborhood, a cell keeps its neighbors from iteration to iteration. All the connections to direct neighbors that it has in one iteration it will still have in the next iteration. Only the division or the removal of a neighboring cell will result in a change of its set of neighbors.

In a simulation with dynamic cell neighborhood, the neighbors are re-established in every iteration according to distance and neighbor count. A dynamic cell neighborhood allows for changes in the network graph and for behaviors like cell migration or the merging and separation of adjacent cell agglomerations.

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Figure 1.
Cellular growth structure

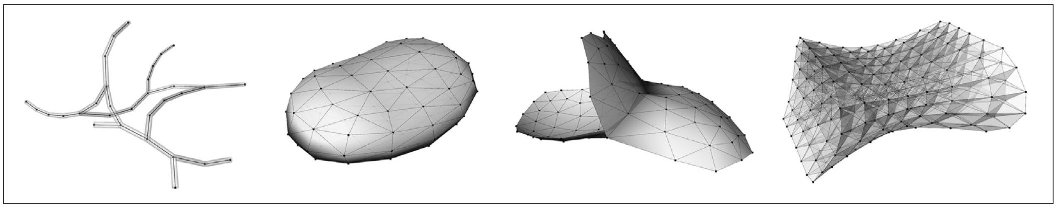

Figure 2.
Structural typologies: Linear system, surface-based manifold system, surface-based non-manifold system, volumetric system

Attraction Force	Cells move towards each other.
Repulsion Force	Cells move away from each other.
Spring Force	Cells attempt to stay at a defined distance.
Planarization by attraction force	Cells generate local planarity through a combination of attraction between neighbors and repulsion towards non-neighbors.
Planarization by local normal force	Cells generate local planarity by moving towards the plane through their closest neighbors.
Strata Force	Cells generate parallel strata by moving towards a plane through their closest neighbors that is oriented along a globally defined normal.
Orthogonal Force	Cells generate orthogonal planes by moving towards the XY, XZ or YZ plane through their closest neighbors that is oriented closest to the cell's local plane.
Attribute Force	Cells react to additional attributes of their neighbors such as an assigned vector.
Drag	Drag slows down a cell's velocity.
Unary Force	A unary force such as gravity acts equally in space.
Position dependent directional force	A vector field has varying directions and strengths depending on the location in space.
Object forces	Attraction or repulsion forces towards objects in space.

Table 1.
Intercellular and External forces

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3.2 Structural Typologies

The simulation can be set up so that the cells form linear chain-like accumulations, accumulations based on single-layer surfaces, or they can form volumetric accumulations (Figure 2):

Cells in linear cellular systems are arranged to form chain-like formations. Examples are the venation networks developed with the algorithm of the University of Calgary (Runions et al. 2005, Runions et al. 2007, Runions 2008). Possibilities of branching or network formations exist if some cells have more than two neighboring cells. (Figure 2a). In a surface based manifold cellular system, all cells are arranged on a single surface, similar to the vertices of a manifold mesh. Examples are the models as described by Hart and Lomas (Hart 2009, Lomas 2014). (Figure 2b). In a surface based non-manifold cellular system, cells have several neighboring cells that they are surrounded by and which tend to locally lie on a surface. However, they do not form a manifold closed mesh and can have open edges or intersect each other (Figure 2c). In volumetric cellular systems, cells form volumetric instead of mono-layer arrangements, similar to the way that multiple cell compounds make up most living organisms (Figure 2d).

3.3 Developmental Typologies

The simulations can develop in different ways over time: The main focus of a simulation can be on growth, on decay or on the reconfiguration of the cellular accumulation. Simulations may commonly be a combination of those typologies. Due to the large amount of possible morphologic variations, most of the examples of this paper are surface-based growth systems. However linear and volumetric systems have also been explored.

4 Simulation Behaviors

The following computational set-up and behaviors have been used for the calculation of the simulations:

4.1 Basic set-up

The examples in this paper have been developed using the ICE simulation in Autodesk Softimage and Processing. The simulations are calculated iteratively, the positions of cells are calculated based on their center points in three-dimensional space. In each iteration, a set of forces is used to calculate a cell's next position, and rules for cell proliferation and differentiation are applied.

Every cell has an acceleration and a velocity. In each iteration, the vectors of the forces that are acting on a cell are added as acceleration onto its velocity, and the resulting velocity vector is added to its previous position in order to calculate the new position.

The following intercellular behaviors and external forces can be applied in varying combinations and intensities to the cells (Table 1). The intercellular behaviors can also simultaneously be applied to different groups of other cells, such as the direct neighbors, the neighbors of neighbors, or to cells that are at a certain distance.

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4.2 Intercellular behaviors for linear and surface based simulations

Let a cell have the position C.

The amount of direct neighbors of a cell may vary for different force calculations in the same iteration. Let a cell have n direct neighbors with positions P_r.

$$Let\ a\ point\ or\ vector\ have\ the\ coordinates = \begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix},\ P_r = \begin{pmatrix} P_{r,x} \\ P_{r,y} \\ P_{r,z} \end{pmatrix}.$$

The diameter of a cell, which equals the target distance between neighboring cells, be d.

4.2.1 Attraction force

In order to achieve accumulations of cells that cluster together, rather than individual disconnected cells, neighboring cells can be defined as being attracted to each other.

$$acceleration\ Attraction\ = \frac{1}{n} \sum_{r=1}^{n} \frac{P_r - C}{|P_r - C|^m}$$

with m being an exponent which can be used to control different types of attraction forces (Figure 3)

4.2.2 Repulsion force

In order to generate cell accumulations, cells need to be attracted to each other while at the same time keeping a certain distance between each other. This can be achieved by having an attraction force between neighboring cells while at the same time having a larger repulsion force between them if their distance becomes smaller than d.

$$acceleration\ Repulsion\ = \frac{1}{n} \sum_{\substack{r=1 \\ |C-P_r|<d}}^{n} \frac{C - P_r}{|C - P_r|^m}$$

with m being an exponent which can be used to control different types of repulsion forces (Figure 4)

4.2.3 Spring force

In order to generate cell accumulations, alternatively to the attraction with repulsion for cells closer than d, a spring force can be applied between neighboring cells with d as its rest length. This option was used in the simulations by Hart and Lomas (Hart 2009, Lomas 2014). (Figure 5)

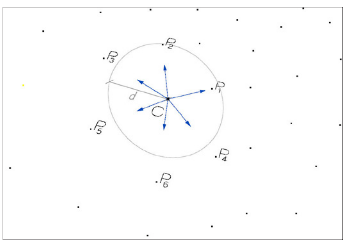

Figure 3.
Attraction force

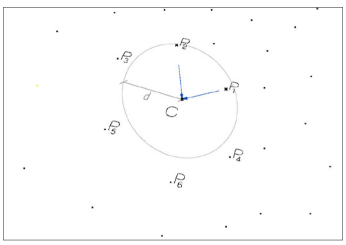

Figure 4.
Repulsion force

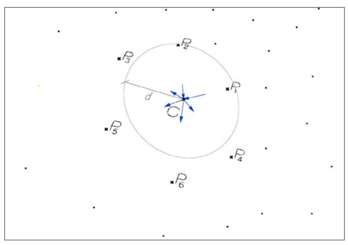

Figure 5.
Repulsion force

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$$acceleration\ Spring = \frac{1}{n}\sum_{r=1}^{n}(d - |P_r - C|) \cdot k \cdot \frac{C - P_r}{|C - P_r|^m}$$

The spring constant k of Hooke's law can vary between different types of cells (Fenster & Ugural 2011). The exponent m can be set to 1 for springs which are acting linearly proportional to their displacement as in Hooke's law, or otherwise to define non-linearly acting springs.

4.2.4 *Planarization by attraction force*

Surface-based cellular systems require a force to generate local planarity, so that volumetric accumulations of cells are avoided. In surface based manifold systems as described in 3.2, which have a static cell neighborhood and no edge conditions, this can be achieved through a combination of an attraction force between neighboring cells and a repulsion force between non-neighboring cells (Figure 6).

4.2.5 *Planarization by local normal force*

For surface-based non-manifold systems as described in 3.2, a planarization by attraction force will cause cells at edge conditions to only be pulled inwards so that the whole geometry continuously contracts. To avoid this, alternatively cells can be pulled towards the plane through its three closest neighbors (Figure 7).

$$acceleration\ Planar = \left(\widehat{(P_2 - P_1) \times (P_3 - P_1)}\right) * -1 * \left((C - P_1) \cdot (\widehat{(P_2 - P_1) \times (P_3 - P_1)})\right)$$

4.2.6 *Strata force*

In order to generate parallel strata of cells, in an architectural context for example for the generation of parallel floor plates, a strata force can be applied to the cell. The direction of the strata is defined by the given normal N. A plane is defined with the normal N and with its origin at the center of the cell's neighbors. The strata force then pulls the cell towards the closest point on this plane (Figure 8).

$$accelerationStrata = \left[N \cdot \left\{\left(\frac{1}{n}\sum_{i=1}^{n} P_i\right) - C\right\}\right] \cdot N$$

In the case of layers parallel to the YZ-plane, $N = \begin{pmatrix}1\\0\\0\end{pmatrix}$*, the force is*

$$accelerationStrataYZ = \begin{pmatrix}\left(\frac{1}{n}\sum_{r=1}^{n} P_{r,x}\right) - C_x \\ 0 \\ 0\end{pmatrix}$$

4.2.7 *Orthogonal force*

A force can be applied to the cells that directs them into orthogonal arrangements. This can be done via identifying the plane of the cell's local environment, the plane that passes through its three closest neighbors. Depending if this plane's orientation is closest to the XY, XZ or YZ plane, a force is applied along the normal $N=\hat{Z}$, $N=\hat{Y}$ or $N=\hat{X}$ respectively. A plane is defined with the normal N and with its origin at the centre of the cell's neighbors. The orthogonal force then pulls the cell towards the closest point on this plane (Figure 9).

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Let M be the normal of the plane through the cell's three closest neighbors:

$$M = (P_2 - P_1) \times (P_3 - P_1)$$

From this, select the coordinate axis s that represents the maximum of the coordinate values:

$$M_s = \max(|M_x|, |M_y|, |M_z|)$$

If, for example, s=x, then the YZ plane is regarded as the best fitting orthogonal plane and the orthogonal force pushes C in direction of the plane with normal N through the centre point of all of its neighbors.

$$N = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

Thus the force according to 4.2.6 would be

$$accelerationOrthogonalYZ = \begin{pmatrix} \left(\frac{1}{n}\sum_{r=1}^{n} P_{r,x}\right) - C_x \\ 0 \\ 0 \end{pmatrix}$$

4.2.8 Attribute force

A cell can have information attributed to it that can define a force or a behavior acting on its neighbors. A cell's movement is then influenced by the attributes of its neighboring cells. This can be used to create effects similar to the alignment as in the Boids algorithm (Reynolds 1987).

$$accelerationAttribute = \frac{1}{n}\sum_{r=1}^{n} A(P_r)$$

with A being the force vector which is attributed to a cell (Figure 10). Green vectors are attributed to a cell and applied to its neighbors.

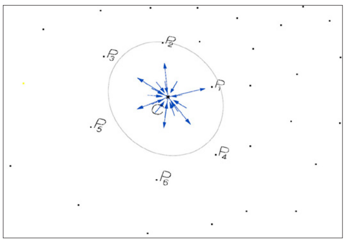

Figure 6.
Planarization by attraction force

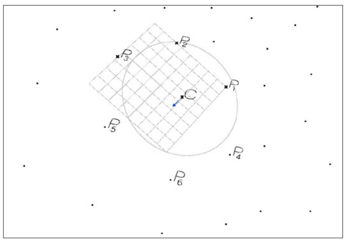

Figure 7.
Planarization by local normal force

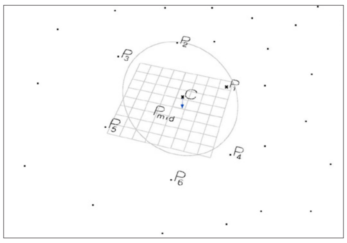

Figure 8.
Strata force

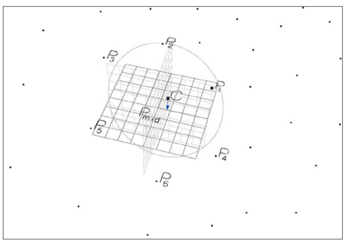

Figure 9.
Orthogonal force

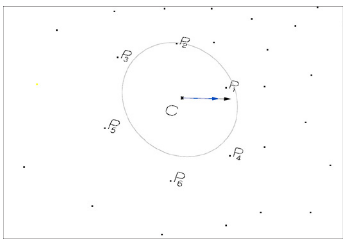

Figure 10.
Attribute force.

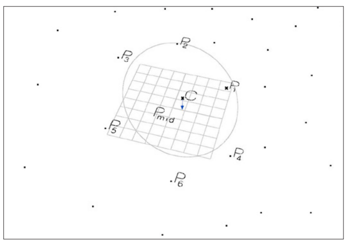

Figure 11.
Drag

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4.2.9 Drag

Drag, a direction dependent factor, can be applied to the cells, especially in order to avoid excess cell movement. Drag is mainly used to reduce the cell velocity.

$$velocityAdjusted = \begin{pmatrix} velocityX \cdot a \\ velocityY \cdot b \\ velocityZ \cdot c \end{pmatrix}$$

with a, b, c being factors in each Cartesian direction. (Figure 11)

4.3 External Forces

External forces are not related to a cell's neighborhood, but usually to the cell's location in space.

4.3.1 Unary Force

A unary force can be applied to the cells, for example to simulate gravity:

$$accelerationUnary = \begin{pmatrix} U_x \\ U_y \\ U_z \end{pmatrix}$$

with U_x, U_y, U_z being the forces in each Cartesian direction (Figure 12).

4.3.2 Position dependent directional force

A position dependent directional force can be applied to the cells. This force can be given by an external vector field V that defines varying vectors depending on a cell's position in space. (Figure 13)

$$accelerationField = V(x, y, z)$$

4.3.3 Object forces

Various external forces and movement restrictions can be applied, such as attraction and repulsion towards geometric objects, forces or movement restrictions which act within certain areas of the world space or which act on selected cells (Figure 14).

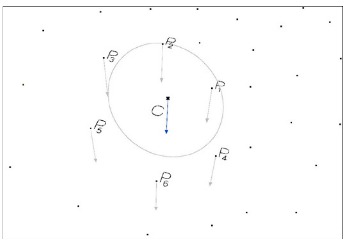

Figure 12.
Unary force

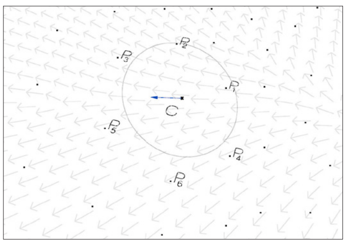

Figure 13.
Position dependent force

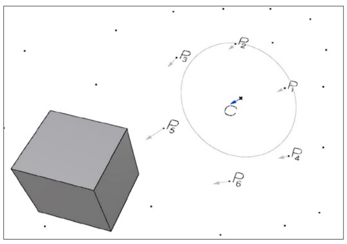

Figure 14.
Object force

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4.4 Intercellular behaviors for volumetric cellular simulations

Volumetric cellular simulations do not use generally applied planarity forces as described in points 4.2.4 and 4.2.5. Component thickness, which is a driving factor for the development of morphogenesis, can be identified by the differentiation of surficial versus interior cells. The amount of neighboring cells in one cell's proximity can be used to evaluate the component thickness.

4.5 Cell Proliferation

Cell proliferation is controlled by the trigger of the division as well as by the local positioning of the child cell. A division triggers can be age, resulting in an evenly distributed growth of the system. In order to generate a marginal growth that extends the agglomeration on its outer edges, two types of triggers have been used: A trigger based on the distance to a cell's neighbors, and a trigger based on the amount of direct neighbors. Both attempt to identify the cells on the edges of the agglomeration for proliferation. The position of a cell in space or its proximity towards external geometries, can be used to enhance or inhibit the cell's proliferation behavior. The local direction of the cell division process can be used to influence the edge conditions of the structure, for example to create a smooth or serrated edge.

4.6 Cell Differentiation

Cells can be programmed to take on specific functions and behaviors. A cell type can be defined at the beginning of a cell's existence, or a cell can change its type according to a trigger. Cell differentiation has been used in the examples of this paper to define cells that have location constraints or are fixed in space, or cells that are constrained in their movement. Cell differentiation has also been used in the volumetric simulations to define interior cells, surficial cells and cells with the possibility to divide.

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5 Results

5.1 System with planarity force

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Spring force towards direct neighbors	strength 0.2, d=0.0, m=2.0
• Planarity by local normal force	strength 0.9
Trigger for cell division	less than 3 direct neighbors

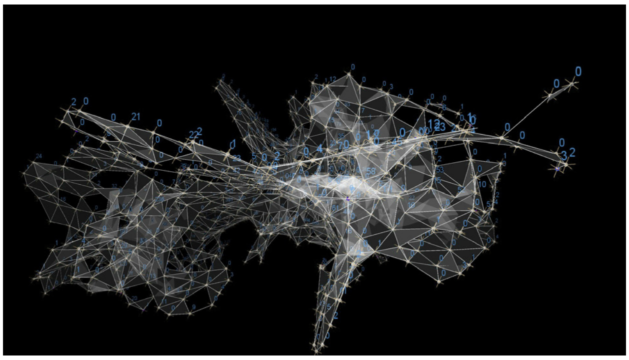

Figure 15.
A basic surface based non-manifold system with planarization by local normal

5.2 Surface-based manifold growth

Cell neighborhood	static
Structural typology	surface-based manifold
Forces acting	
• Spring force towards direct neighbors	strength 1.0, d=1.0, m=5.0
• Repulsion towards cells closer than 10.0	strength 5.0
• Planarity by local normal force	strength 1.0
• Normal force	strength 1.0
• Unary force	z=-0.1
• Drag	0.2
Constraints	ground surface
Trigger for cell division	random uniform

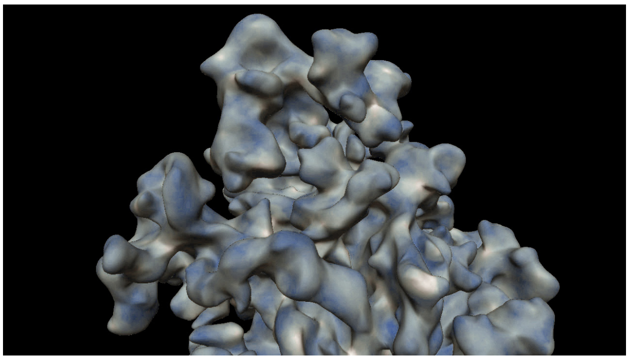

Figure 16.
A surface-based manifold growth simulation

5.3 System with unary force

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 1.0
• Planarity by local normal force	strength 0.5
• Unary force	z=-0.01
• Drag	0.5
Constraints	ground surface
Trigger for cell division	average distance >1.5 for 2 closest cells

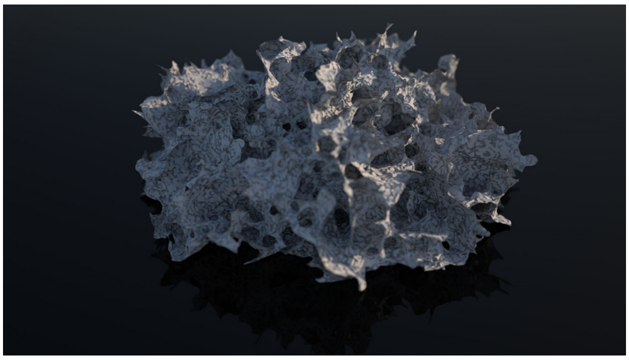

Figure 17.
A surface based non-manifold system with planarity force, unary force and a surface boundary condition.

5.4 Shell structures

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.2
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Repulsion towards cells closer than 5.0	strength 0.5
• Planarity by local normal force	strength 1.0
• Surface force	strength 0.1
• Unary force	z=-0.1
• Drag	0.1
Trigger for cell division	less than 3 cells at a distance of 1.5

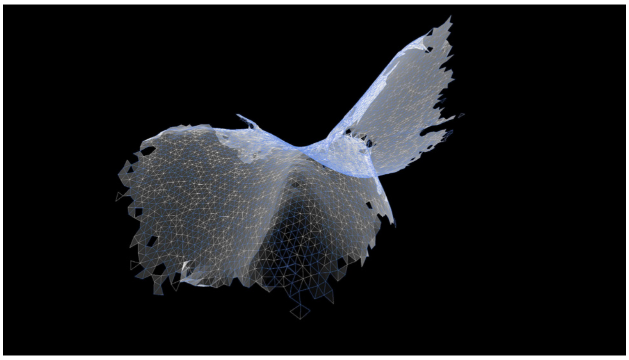

Figure 18.
Shell structure, generated by using gravity in combination with movement constraints for specific cells.

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5.5 Horizontal strata

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.2
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Repulsion towards cells closer than 5.0	strength 0.5
• Planarity by local normal force	strength 1.0
• Strata force	strength 0.04
• Unary force	z=-0.1
• Drag	0.1
Trigger for cell division	less than 3 cells at a distance of 1.5

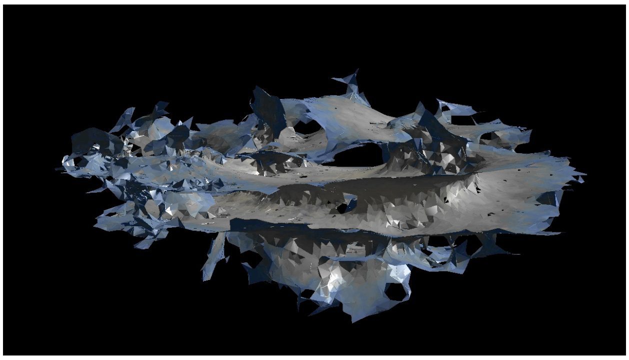

Figure 19.
A surface based non-manifold system with strata force. The cells agglomerate in parallel orientated fieldsthat form at roughly equal distances

5.6 Orthogonal structure

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.4
• Repulsion towards direct neighbors closer than 1.0	strength 2.2
• Repulsion towards cells closer than 5.0	strength 1.1
• Planarity by local normal force	strength 0.5
• Orthogonal force	strength 0.1
• Unary force	z=-0.1
• Drag	0.1
Constraints	containing box
Trigger for cell division	average distance >5.0 for 2 closest cells

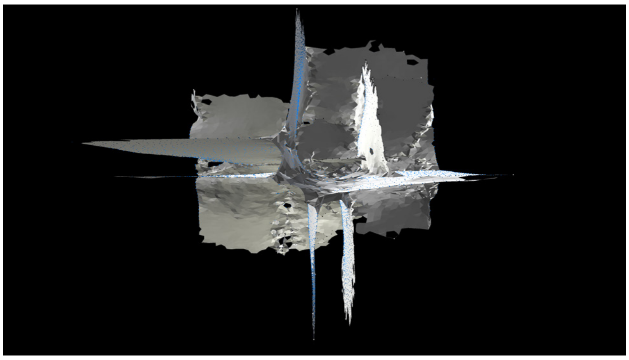

Figure 20.
A surface based non-manifold system with orthogonal force. The system is constraint to a rectangular volume

5.7 Network generation

Cell neighborhood	dynamic
Structural typology	linear
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 2.0
• Planarity by local normal force	strength 0.5
• Surface force	strength 0.3
• Drag	0.1
Trigger for cell division	less than 2 cells at a distance of 6.0

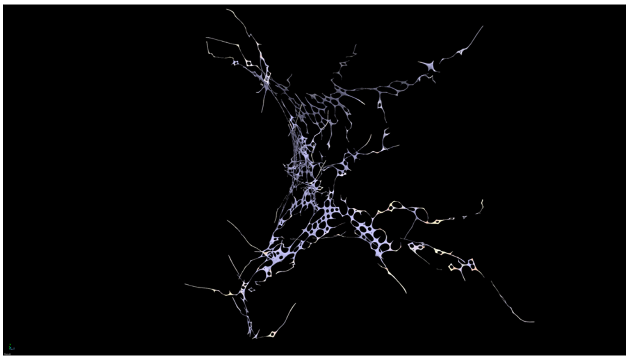

Figure 21.
Network morphology generated through a linear growth of the cells. A dynamic cell neighborhood allows cells from different strands in close proximity of each other to connect in order to form loops

5.8 System with volumetric accumulation

Cell neighborhood	dynamic
Structural typology	volumetric
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Drag	0.2
Trigger for cell division	less than 7 cells at a distance of 2.0

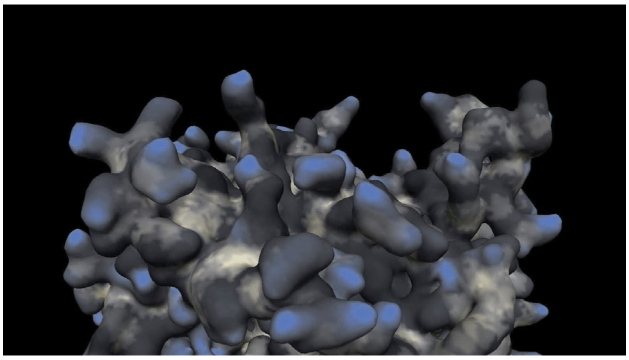

Figure 22.
A volume based system with cell proliferation defined by cell neighborhood

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5.9 Reaction diffusion patterns

Cell neighborhood	dynamic
Structural typology	volumetric
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Drag	0.2
Trigger for cell division	less than 7 cells at a distance of 2.0

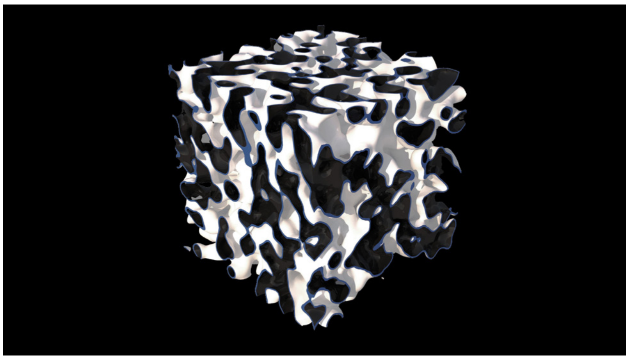

Figure 23.
A volume based system with patterns similar to reaction diffusion systems

5.10 Attribute force to control cell proliferation

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 1.0
• Planarity by local normal force	strength 0.5
• Attribute force	average of 5 closest cells at creation
• Drag	0.5
Trigger for cell division	average distance >1.5 for 2 closest cells

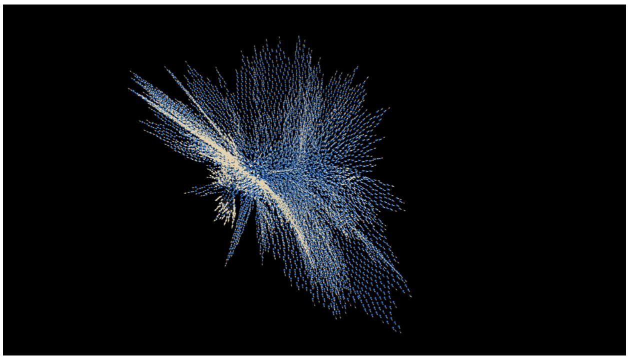

Figure 24.
A surface based non-manifold system. The proliferation direction is influenced by the neighboring cell's attributed vector

5.11 Vector Field as cellular force

Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.5
• Repulsion towards direct neighbors closer than 1.0	strength 2.0
• Repulsion towards cells closer than 5.0	strength 1.0
• Planarity by local normal force	strength 0.5
• Unary force	z=5.0
• Vector field force	strength 10.0
• Drag	0.5
Trigger for cell division	average distance >1.5 for 2 closest cells

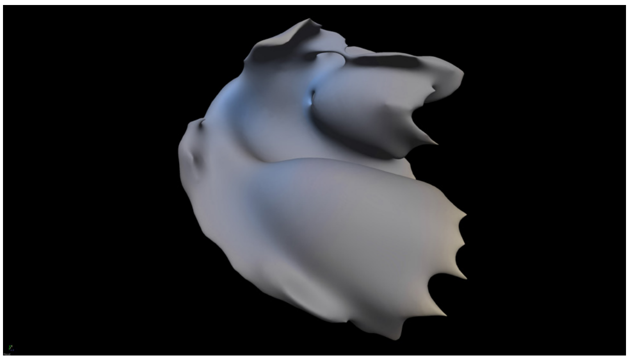

Figure 25.
A surface based non-manifold system. A unary force in combination with an attractor based vector field are acting on the movement of the cells

5.12 Procedural cavitation

Cell neighborhood	dynamic
Structural typology	surface-based non-manifold
Forces acting	
• Attraction towards direct neighbors	strength 0.2
• Repulsion towards direct neighbors closer than 1.0	strength 1.0
• Repulsion towards cells closer than 5.0	strength 0.5
• Planarity by local normal force	strength 1.0
• Unary force	z=-0.1
• Drag	0.1
Trigger for cell division	average distance >1.5 for 2 closest cells and less than 3 cells at a distance of 1.5

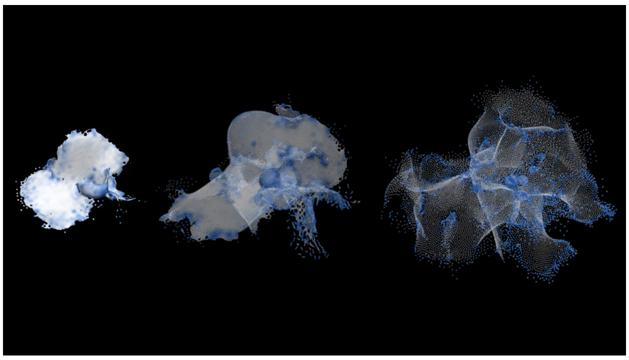

Figure 26.
Procedural cavitation generated through an increased contraction of peripheral cells. 3 stages of a simulation from left to right: The first semi-enclosed bowl-like cavitation; the first fully enclosed cavity with a second one forming at the top left; a later stage with several fully enclosed cavities

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6 Design Applications

The proposed simulations have been applied to the design of two case studies: The design of a permanent installation in an office, and the design of an unbuilt house.

6.1 Gaizoshoku

The installation Gaizoshoku has been designed and constructed for the offices of IT company Baishan in Beijing and incorporates the company's reception area and desk. Various requirements had to be taken into account for its design, such as structural stability, human circulation around the structure, access to the surrounding spaces and the lighting conditions that the installation creates. Instead of generating a geometry and post-processing it to fit those needs, all of the requirements have been translated into intercellular behaviors and external influences. Due to the highly emergent nature of the growth simulations, the fine-tuning of those behaviors was a time-consuming process that required extensive re-running of the simulations with slightly adjusted parameters in order to guide the geometry into its required form. It was nevertheless possible to achieve a suitable geometry solely through the simulation process, that at the same time generated a very characteristic geometry.

The growth simulation started at the bottom with a tendency to grow upwards. A central vertical line acted as an attractor that decreased in strength towards the top, while also the rough outline of the reception desk attracted cells. A strata force was used to generate parallel horizontal layers, with its strength increasing towards the top, thereby creating a relatively flat layer below the ceiling and more curving and inclined layers further down. Those forces then resulted in a geometry that allows for human circulation around it while still creating the desired surface and lighting effects above. Gaizoshoku was then constructed out of polypropylene sheets and assembled on site (Figure 27).

6.2 Ntopios

For the design of the house Ntopios, the client asked for a free form design that can be built using a cellular fabrication system of robotically extruded polymer. Instead of designing a geometry that can be built using the technology, Ntopios incorporated the logic of formation into the robotically constructed lattice system. The basic behavior of every cell to keep a specified distance towards its neighbors was used to generate the required regular lattice for the extrusion, while other behaviors cause the cells to form horizontal floor plates, enclose volumes with roofs and create a network of interconnected spaces with a useful circulation.

The algorithm has been successful in generating the geometry of a functional single family house with living, sleeping and auxiliary spaces. A strata force was used to create the horizontal surfaces for floors and roofs, while the resulting inclined areas between them form the vertical circulation. The cell division was terminated once large enough spaces had been generated. The grown lattice itself, which forms the logic of the robotic cellular construction system as well as the logic of the house, is also being used as the defining aesthetic element. It is exposed underneath the ceilings and continues out of the walls as furniture (Figure 28 & 29).

Compared to Gaizoshoku, the design of Ntopios required much less experimentation with the simulation parameters and relatively quickly resulted in a geometry that was suitable for the project. However, the design remained conceptual only and did not move to the construction stages.

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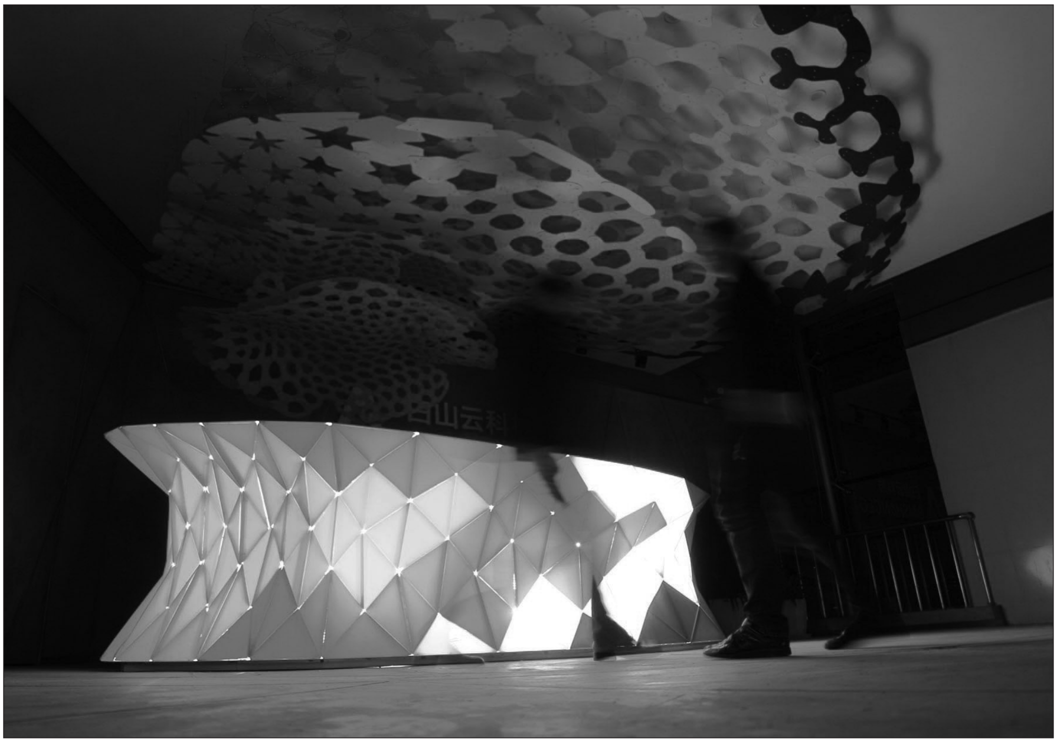

Figure 27.
Gaizoshoku

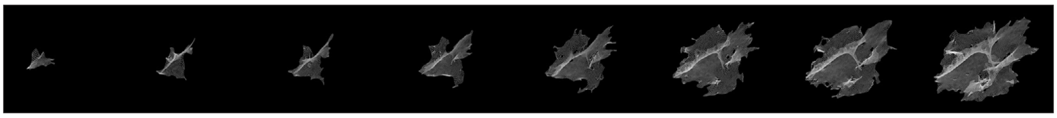

Figure 28.
Ntopios, cellular growth development.

Figure 28.
Ntopios, cellular growth development.

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7 Conclusions and future work

The The cellular growth simulations presented in this paper provide a novel tool for the computational generation of form for art and architecture. The proposed algorithms have been shown to be able to generate a wide variety of morphologies many of which show characteristics relevant for architectural applications.

The generalizations from previous work, especially the possibilities of surface-based non-manifold geometries and of volumetric geometries, allow for morphologies such as open geometries, multiple-cavity formations or continually expanding systems, which all provide important arrangements for the development of architectural space.

The results show that the growth simulations can generate networks, surfaces and volumes. Different degrees of enclosure can be created. The generation of parallel and orthogonal surfaces can be used as floor, wall or structural systems. Specific structural behaviors can be generated by applying gravitational forces onto the system. The morphologies can be free-form but can also be programmed to follow rectangular or other geometric systems. Various types of patterns, often organic or fractal in nature, can be generated on a small as well as a large scale.

It has been found that the intercellular behaviors have a high degree of emergence (Kwinter 2008). Due to this implicit rather than explicit nature of the systems (Liaropoulos-Legendre 2003), already small changes to the variables can result in very different outcomes. This makes it more difficult to generate a specific preconceived outcome, but it allows for unexpected characteristics of the resulting geometry. One of the main tasks for further development will therefore be the creation of mechanisms that let a user more easily influence the design outcome. The external influences on the contrary can very easily be set up to guide the growth of the cells towards a required overall geometry. Further research could therefore focus on the use of attractors, imported geometries as attractors and imported geometries as areas that constrain cell movement.

Also a growth according to structural constraints could be explored, with the aim of generating geometries that are suitable as load-bearing systems. The cell network could be analyzed iteratively as a Finite Element system, with the cells reacting locally to the forces or deformations that are identified.

On a programmatic level it would be of interest to further explore the generation of enclosed spaces and their relation to each other, possibly similar to the way that the cells in an embryo start to form separate cavities and later organs. This could lead to a tool for space planning in order to develop occupiable spatial arrangements.

Acknowledgements
The projects Gaizoshoku and Ntopios were carried out in collaboration with Rajat Sodhi and Satoru Sugihara.

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ISSN 2309-0103
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