Discrete Cellular Growth

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ABSTRACT
The use of time-based computational simulations in architectural design has led to highly complex geometries; however, those often are difficult to construct. In order to generate more easily buildable structures, we therefore attempted the integration of the placement of identical discrete components into a time-based growth simulation. We present a research project focusing on computational cellular growth which simulates the development of organisms as accumulations of cells, discretization of the resulting surfaces, and their construction through prefabricated components. Different intercellular behaviors as well as external forces acting onto the cells were explored during the design process. One of the outcomes was constructed physically as a 1:1 large-scale prototype and compared to a free-form structure that was generated by a similar growth simulation. The placement of the components results in geometries that still share many of the qualities of the previous free-form growth structures, but which at the same time exhibit distinct geometric behaviors of their own.

1 INTRODUCTION
Architectural designers have used various time-based computational simulations to generate highly complex geometries (Stuart-Smith 2016, Snooks 2013, Andrasek 2012). However, the results often pose the difficulty of a feasible construction. The generated geometries are often free-form without any repetition of elements or curvature, often combined with a high degree of intricacy. Architects have therefore often not been able to realize designs that have been generated with time-based simulations, or have done so only at a smaller scale with methods such as 3D printing or a tessellation of complex geometry into simpler surfaces.

In order to generate more easily buildable structures, we attempted the integration of the placement of identical discrete components into a time-based growth simulation. We present a research project focusing on computational cellular growth which simulates the development of organisms as accumulations of cells, discretization of the resulting surfaces, and their construction through prefabricated components. One

Figure 1: Bryx Front View

of the successful outcomes was constructed physically as a 1:1 large-scale prototype (fig. 1). We compare this prototype with a previous project that was based on the same generative growth algorithm, but that was translated into free-form tessellated surfaces for construction (Klemmt and Sugihara 2018). Different intercellular behaviors as well as external forces acting onto the cells were explored during the design process of both projects.

The placement of the components results in geometries that still share many of the qualities of the previous free-form growth structures, but which at the same time exhibit distinct geometric behaviors of their own.

2 RELATED WORK

Since the introduction of computational tools in architectural design, many architects and designers have been interested in the simulation of time-based processes via iterative algorithms. Those include mathematically abstracted systems such as cellular automata (Wolfram 1983) but, more commonly, systems that aim to simulate behaviors and processes that occur in the natural world. Often those are based on the movement, division, or other behaviors of programmed particles or agents. Swarm simulations, which can recreate the movement patterns of social animals, have been used by various architectural designers to create arrangements in space or by tracing the movement paths of the individual agents (Snooks 2013; Stuart-Smith 2016; Andrasek 2012). Differential growth is based on the division and proliferation of particles that maintain specified relations towards their neighbors and has been used to computationally "grow" complex geometries (Louis-Rosenberg 2015; Bader et al. 2016). Recursive subdivision is based around the repositioning and insertion of new vertices into an initially simple mesh geometry in order to refine its shape (Hansmeyer 2010; Hansmeyer and Dillenburger 2013).

Different methodologies have been utilized for the construction of the complex geometries at the installation or building scale resulting from those or related generative processes. While there are many possibilities, some of the commonly used methods are 3D printing, CNC cutting, or a tessellation into smaller components. 3D printing has so far mostly been applied at a smaller scale. Large-scale examples include (Ruffray et al. 2017; Yu 2017; Chiusoli 2018). 3D CNC cutting of components has been used for the Armadillo Vault by ETH Zurich's Block Research Group (Block et al. 2017). The tessellation of a complex geometry into smaller, possibly only flat or single-curved segments, has been used at various scales. Or1 by Orproject was the first single surface constructed in this way (Fairs 2008), a method that has since been used by various architects (Fornes 2015; Thiemann 2011). At the large scale, several of Zaha Hadid's double curved building facades are broken down into mostly flat or single curved panels (Ceccato 2012). In all of those cases, the final overall form will still be a double curved freeform geometry.

On the contrary, the other possibility is to work with discretized or voxelized geometries. In this case, either the overall form is built up of repetitive identical components, or a complex geometry may be rationalized into the repetitive units. In a voxelized geometry, it is possible to base the discretization on an underlying spatial 3D grid so that every component fills a 3D grid cell or voxel. Those could be cubes, but other spatial grids can also be used (Retsin 2016). Alternatively, a component could have any shape, but with specific connection points toward its neighbors that define how multiple components can be arranged (Sanchez 2016).

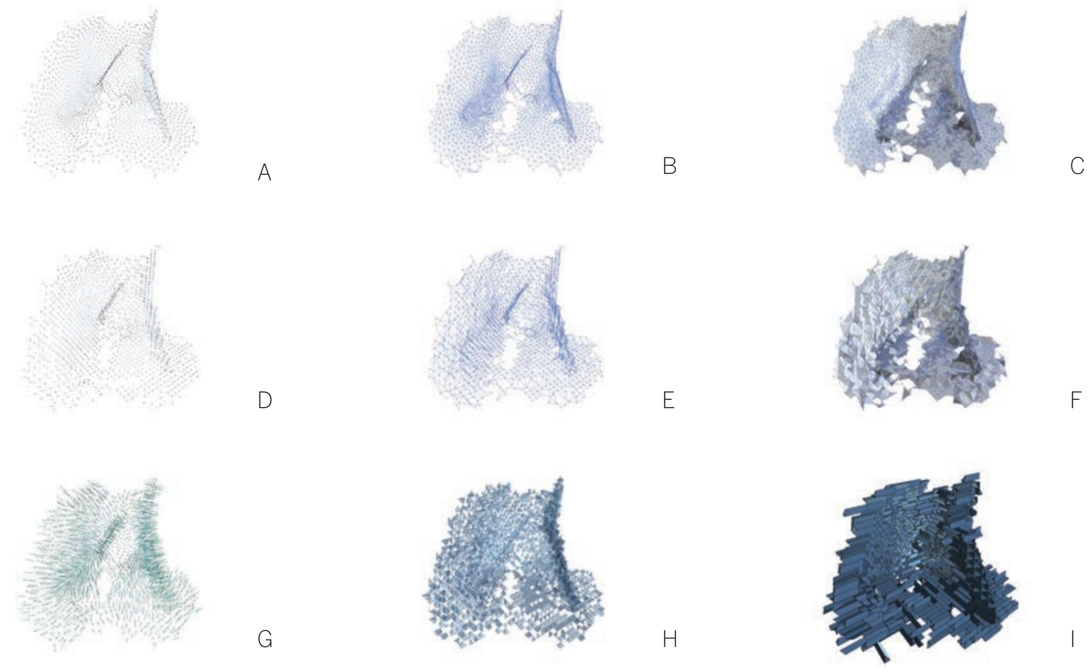

Figure 2: Cellular Growth: A) Cell Accumulation. B) Range of Influence. C) Cell Neighborhood. D) Cell Connections. E) Division Triggers. F) Voxel Grid. G) Occupied Voxels. H) Component Placement. I) Components.

For this paper, our interest lies in the comparison of the freeform and the voxelized construction methods, specifically in the use of the tessellation of a complex geometry versus a construction of a voxelized form, both generated through closely related growth algorithms.

3 GROWTH SIMULATIONS

Cellular growth simulations attempt to computationally simulate the growth processes of entities that are made up of multiple individual cells (Lomas 2014; Bader et al. 2016; Louis-Rosenberg 2015). The simulations start with a small amount of initial cells. The growth and the development of the form are based on cell proliferation, cell differentiation, and morphogenesis. Programmed as point clouds, the cells are subdividing and taking on specific functions within the larger accumulation. During the growth, the cells react highly emergently according to intercellular behaviors toward their neighbors, as well as to global location-dependent forces. Those behaviors and forces then shape the resulting geometry (Klemmt 2019).

Algorithmically, the cells are calculated by X, Y and Z coordinates in 3D space. In every iteration, first the cell neighborhood is recalculated: Every cell defines which other cells it regards as its neighbors according to their proximity and according to a maximum number of neighbors. Cells can therefore start or cease to be neighbors from one iteration to the next if they move within or past the maximum range. A cell's neighbors will then influence its movement and division behavior (fig. 2).

Figure 3: Gaizoshoku Side View.

Figure 4: Gaizoshoku Detail

3.1 Cell Movement

Different forces are controlling the movement of the cells and are added up as vectors as the cell's acceleration. The previous velocity of the cell is reduced by a drag factor, then the acceleration is added to it. The velocity is then added to the previous position of the cell in order to define its new position.

The cells represent units with an approximately spherical volume. The center points of the cells therefore need to stay at a distance close to the intended diameter of the cells. In order to achieve this, a neighbor force is acting between adjacent cells. This force pushes cells further apart if their distance is closer than the defined target distance, and it pulls cells together if their distance is larger. The further two cells are positioned from each other, the smaller the influence of this force.

A planarity force causes the cells to locally arrange within surfaces, rather than to form volumetric clusters. This force functions by identifying the local plane of the cell, the plane that passes through the three closest neighbors of the cell. The cell is then pulled onto this plane along the plane's normal vector.

Other forces that have been explored include a strata force, which causes cells to arrange along parallel surfaces. An orthogonal force causes cells to arrange along orthogonal planes. Gravity pulls the cells downwards. Attractor forces cause cells to move toward or away from a point depending on their proximity to it. Object forces cause cells to move toward or away from imported mesh geometries. Constraints or obstacle objects prevent cells from moving into restricted areas in space.

3.2 Cell Division

Various triggers can cause cell division; however, for both of the presented case studies, the aim was to identify cells on the margins of the accumulation for division so as to grow the structure outwards. The marginal cells were identified by the distance to their closest neighbors: A centrally positioned cell will have neighbors all around it and therefore a smaller average distance towards its neighbors than a cell on the edge.

Upon being identified for division, a new cell is inserted into the model adjacent to the dividing cell. Additional rules for the direction and velocity of the parent and child cells after division will have an influence on the edge conditions of the accumulation.

4 GEOMETRY RATIONALIZATION BY SURFACE TESSELLATION

4.1 Gaizoshoku

The main difficulty of the construction of the resulting, highly complex geometries at an architectural scale is the economic feasibility of the geometries. The previously completed project *Gaizoshoku*, developed by Orproject in collaboration with Satoru Sugihara, was constructed for an office interior in Beijing in 2015. The project utilizes the same growth simulation for the development of its geometry as the below presented project *Bryx*, but without voxelizing the individual cell locations. Instead, the cell locations remain in their freeform position in space, and the translation of cell centers to material happens via their triangulation into mesh surfaces (Klemmt and Sugihara 2018) (fig. 3).

The planarization force that is integrated into the algorithm causes the arrangement of neighboring cells into planar surfaces and in the process assigns each cell a normal vector. Based on those normal, it is now possible to connect neighboring cells into mesh triangles, with the cell positions forming their nodes. For *Gaizoshoku*, those base triangles were further deformed parametrically in order to create a varying opacity of the overall structure. Connections between adjacent panels were placed centrally on the edges of the base triangles so that two panels always meet at one joint, fastened by a set of two bolts (fig. 4).

4.2 Construction

The installation, excluding the reception desk below, was constructed from 2,521 different pieces. Each piece was marked with four numbers: the identifier of the piece in the center and the identifiers of the three adjoining pieces at the corresponding edges. The structure has an area in plan of about 18 m², with a height of about 1.3 m. The construction took about two weeks for a team of six workers, with a cost for construction of only about $10,000.

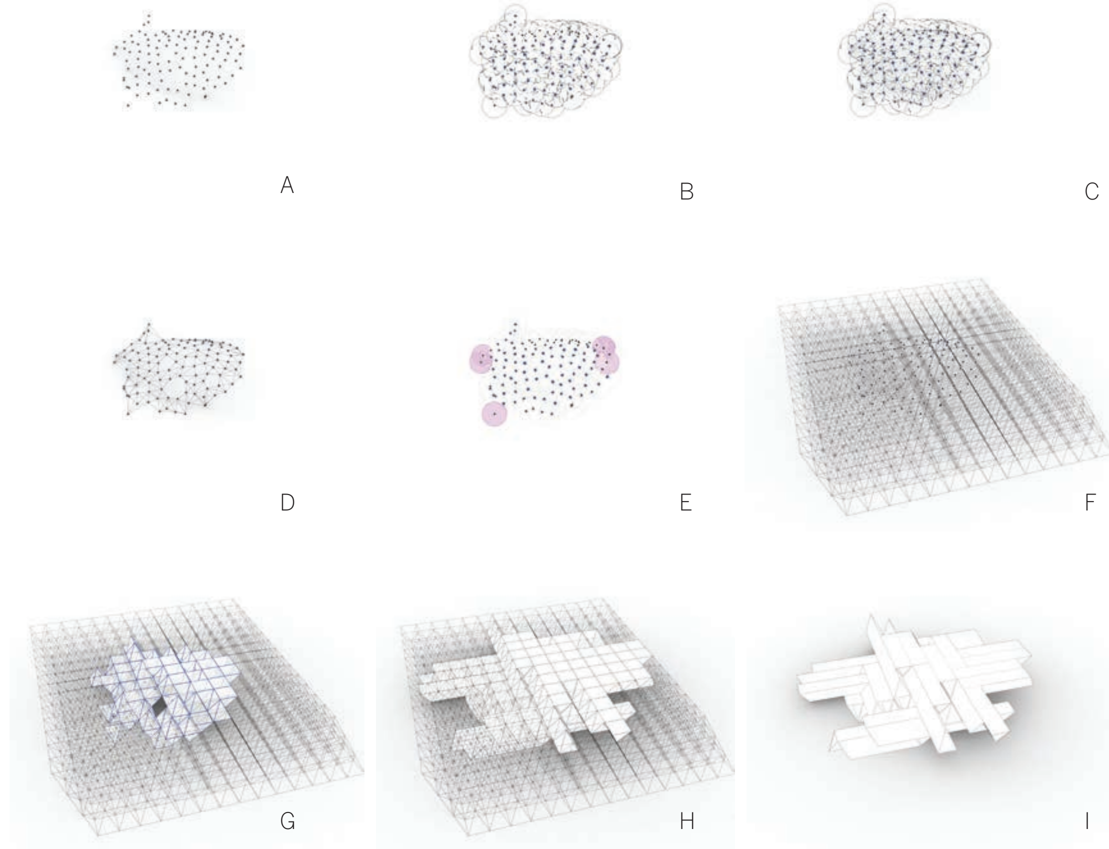

Figure 5: Discrete Growth: A) Cell Accumulation. B) Range of Influence. C) Cell Neighborhood. D) Cell Connections. E) Division Triggers. F) Voxel Grid. G) Occupied Voxels. H) Component Placement. I) Components.

5 GEOMETRY RATIONALIZATION BY VOXELIZATION

5.1 Bryx

Following the discrete paradigm, we used identical components in order to construct a larger assembly of the cells while avoiding techniques, such as panelization or the slicing of surfaces, which would lead to a large number of custom components as in *Gaizoshoku*. This happened through the implementation of a space discretization in the growth simulations so that the resulting geometries can be feasibly constructed from identical components (fig. 5).

The voxelized grid used in the design process is a triangular pyramid grid, which uses alternating pyramid and tetrahedron voxels. The components are an elongated assembly of eight voxels—four pyramids and

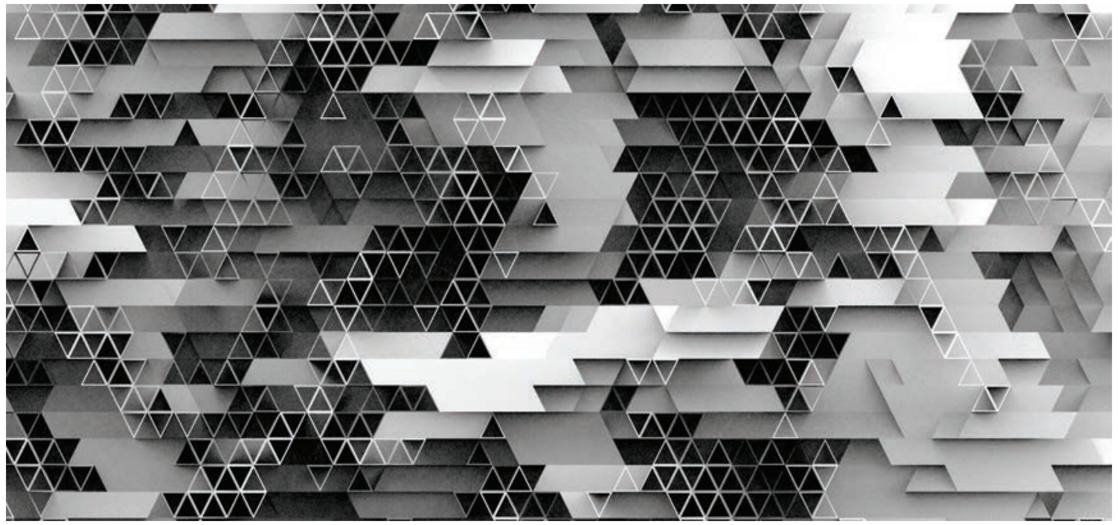

Figure 6: Voxelized Assembly

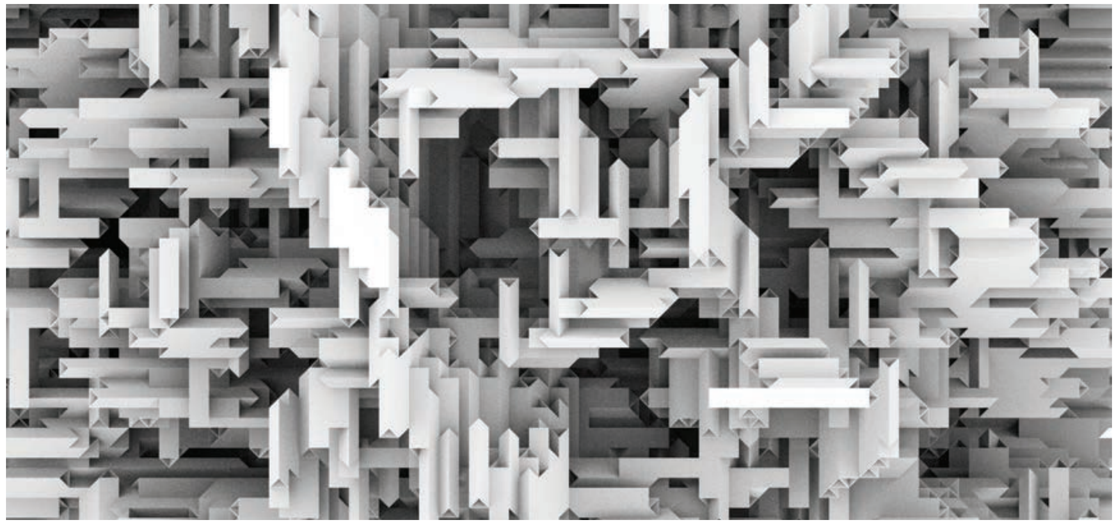

Figure 7: Voxelized Assembly

four tetrahedrons—that together form a triangular tube. Those components are then placed in every iteration of the simulation through the voxels that a cell occupies, with options to vary the component's orientation. All aspects of the algorithmic process—cellular growth, voxelization, and placement/orientation of components—are in mutual feedback, affecting each other throughout the duration of this iterative process (figs. 6 and 7).

5.2 Full-Scale Prototype Fabrication

The prototype was constructed from 450 identical prefabricated components cut out of straight triangular aluminium extrusions that were custom manufactured for this project. The geometry of each component then corresponds to the eight voxels that it occupies in the growth simulation. The use of such discrete elements allowed for economic feasibility and a straightforward assembly process. As all components are identical, there was no need for labelling logistics.

For this project, the components were connected with epoxy glue, although other means of assembly, such as bolts, rivets, or high-strength double-sided tape, could be explored. The assembly process proved to be very efficient, and all 450 components were assembled in less than 12 hours (figs. 8–10).

6 EVALUATION

In order to evaluate these two different methods for materializing surfaces generated on the principles of discrete cellular growth, the prototypes are compared on the qualities of resulting geometries and their differences, as well as the viability of the construction method, including its time, cost, and ease of assembly.

Both installations can be understood as a part or prototype of a larger architectural system. The cellular growth simulation itself produces articulated spatial arrangements with varying degrees of complexity and porosity. The *Gaizoshoku* installation truthfully translates the generated geometries into physical output, with minimal differences between the node positions of the two. This has, however, required a large number of unique pieces, allowing for little tolerance and interchangeability in the construction process, increasing the construction time and complexity. Likewise, the scalability of the material system beyond an installation or a furniture piece can be questioned.

Bryx, on the other hand, compensates the loss of resolution with speed and ease of the construction, thanks to the use of the self-similar and interchangeable discrete elements. The repetition of the components not only simplified their assembly, in which two components always connect in repetitive arrangements, but it especially pertained to the fabrication of the identical components. This could be outsourced to a regular aluminium manufacturer that did not require advanced digital skills. Instead of a need for digital cutting templates, as in *Gaizoshoku*, the simple top, front, side elevations were sufficient to describe the single component type to the factory.

Likewise, materializing the surface through discretization allowed for a more heterogeneous treatment of the surface itself, through change in the porosity, layering, or orientation of the discrete elements along the underlying surface—suggesting that additional spatial qualities, absent from literal translation of the surface topology, could be achieved on an architectural scale. This results in the generation of legible architectural elements of varying porosity, on top of enclosures derived from cellular growth. The resulting formations can, to a certain degree, depart from the underlying surface, as the qualities of generated enclosures are not directly bound to the topology of the surface, but are rather the consequence of local and global patterns formed through the distribution of the discrete components.

The output of the underlying growth algorithm in both cases is a point cloud. It could be argued that in *Gaizoshoku*, this point cloud is interpreted as a surface that can curve to enclose space and form volume and structure, whereas in *Bryx*, the point cloud is interpreted as volume, which is already structural and can be used to form larger structural assemblies and surfaces, and likewise enclose space.

Figure 8: Bryx Side View

Figure 9: Bryx Back View

Figure 10:
Bryx Details

7 CONCLUSIONS

Both *Gaizoshoku* and *Bryx* can be regarded as successful projects in terms of their ability to create a physical construction within a defined budget and time frame. Both were based on the same underlying generative algorithm; however, the means of rationalization for their physical construction were very different, with *Gaizoshoku* using a surface tessellation vs. the discretization used for *Bryx*. Those yielded clear differences on various levels, ranging from aesthetics to ease of construction, and the resulting geometric and spatial qualities. The discrete construction methodology used for *Bryx* appears to be significantly simpler and more economical, and also possibly more easily scalable for building construction. However, for any design task there will be different requirements as well as design intentions from the architect that define how a complex freeform geometry can best be translated into its physical reality.

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