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STRUCTURAL DNA: Genetic Exploration of Biological Micro Structures for Architectural Applications

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Abstract

Complex biological structures, designed by forces of nature, frequently serve as inspiration for new developments in the field of building technology and architecture. Well known examples in the work of Gaudi, Paxton, Otto, Le Ricolais and others demonstrate the inspiration of natural morphology and patterns for structural design. The use of digital technologies to investigate the translation of natural microstructures into architectural macrostructures offers a valuable exploration tool for both designers and engineers working in the field of architecture.

As demonstrated in this paper we present the use of Evolutionary Computation (EC) to enhance and modify structural form based on biological micro structures. The forms

are modified to conform to new boundary conditions associated with architectural structures. The process is based on a Genetic Algorithm (GA), which exposes a range of good performing solutions within the design space to the designer. The application of the GA is combined with parametric software, in this case Generative Components (GC), to allow the designer to navigate through a range of solutions which follow morphological patterns taken from the biological form. The method, referred to in this paper as parametric evolutionary optimization (ParEvO), uses a finite element analysis to determine the structural performance of the forms. This allows the designer to manipulate and optimize a parametrically defined model based on predefined criteria and parameters.

The opportunities and limitations of this design process are explored and evaluated based on an experimental case study using the forms of radiolarian skeletons. Radiolarians are a group of marine protozoa found in the open ocean which have ornate siliceous skeletons. The radiolarians are analyzed in relation to their environment and special qualities. Based on these findings, a parametric model of an architectural, space enclosing structure is defined and used in the ParEvO loop, taking into consideration new boundary conditions and load cases.

By going through a simplified design process of a dome structure inspired by radiolarian skeletons, including the research-, design- and analysis phase, the paper demonstrates how the ParEvO cycle of selection, recombination, and evaluation is used to optimize and explore a large range of solutions. Finally, there is a discussion of the quality of solutions found based on both structural and architectural performance. In conclusion, comments are made regarding the general application of design exploration methods like ParEvO as design tools both in the context of practice and studio.

Introduction

In this paper we present the design exploration of a complex issue, based on inspiration from natural structures. On one hand nature is discussed as a model for extracting meaningful design principles, and on the other hand digital technologies are shown as support in exploring these principles in their complexity.

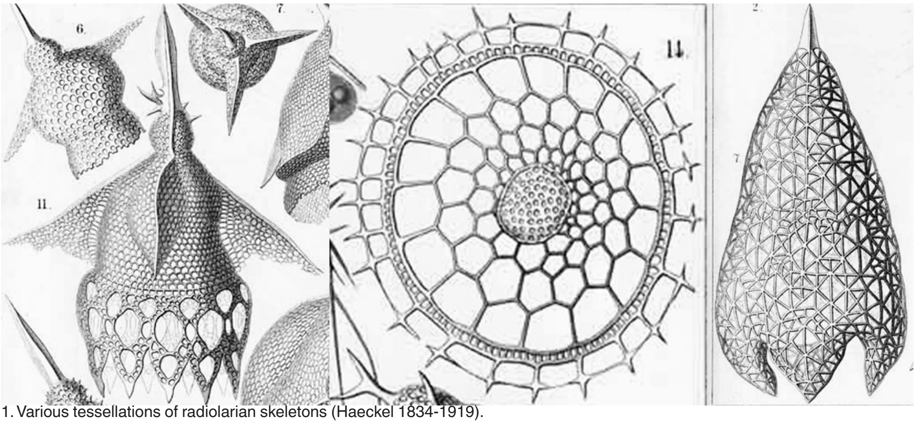
The architectural discipline consists of complex processes of ideation and evaluation. Focusing on geometry, with recent advances in software and technologies, complex geometries and structures are becoming ever more feasible for architects and engineers to explore. In nature we are confronted with the most intriguing examples of efficient structures every day. But it is not only beauty what we experience in natural systems. Their multi functionality appears in many cases to be the result of complex emergent systems. Although these systems are based on clear design models, this organized complexity is hard to comprehend for a human mind, both in its natural state and in a design exploration process. Based on this premise, this research presents a tool to help the designer in exploring optimal or near optimal configurations of organized complexity within the design space. By inserting certain rules, criteria and variables, the designer has the opportunity to evaluate a chaos of possibilities in a specified direction. We will show this process by optimizing a dome structure, inspired by radiolarian characteristics.

In order to explore the structural morphology of the dome its geometry is reconfigured, taking natural structures as inspiration. Computational geometry techniques and genetic algorithms are used to support its exploration. The paper discusses the dual aspects of the work, regarding its contribution to the architectural design activities of teaching and practice. These contributions are proposed as an example of a process of learning from nature, with reference to a meaningful selection of geometrical principles which are explored. The potentials of the digital-based optimization process are shown as a possible method for investigations and evaluations of complex design alternatives. The topic was proposed as a design experience during a master course at the Faculty of Architecture at TU Delft.

The first section of the paper focuses on radiolarian structures and presents a summary of the broad preliminary investigations carried out. The discussion here is kept at a general level by showing the larger research context, while tackling geometrical principles and material conformation of these organic structures. The second section introduces the process of translation from micro organisms to large scale artificial structures and discusses the exploration of a parametric dome using the ParEvO method. Following, the parametric model is described in detail and the optimization method s presented. Results are discussed with respect to both the specific case and the proposed method. Lastly, we will discuss biomimicry as a design approach and the described computational method are proposed for further applications.

Radiolarians' structures: general investigation on principles, geometry and materials.

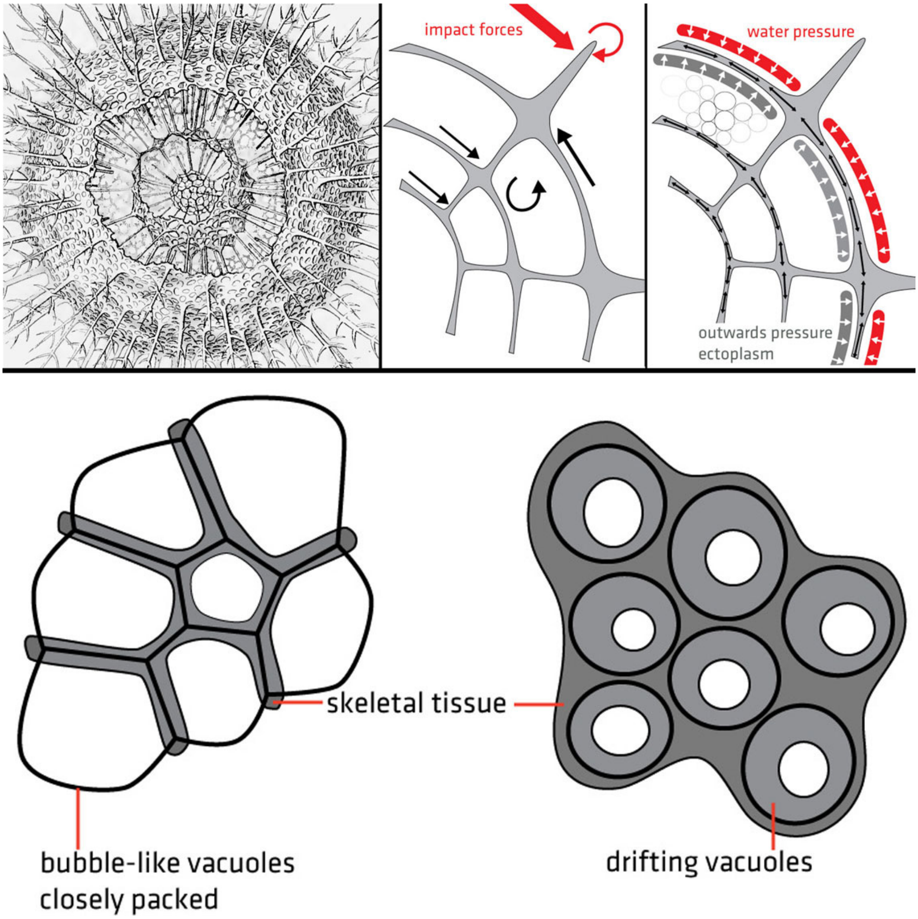
Focusing on the unicellular species of radiolarians, it is apparent that in spite of their comparative simplicity and minuteness, radiolarian skeletons exhibit extraordinary delicacy (Figure 1). Their lightness seems to show great efficiency of structural performance. The structural behavior of radiolarian skeletons is similar to that of soap bubbles, cellular structures and even molecular structures. The principle of surface-



1. Various tessellations of radiolarian skeletons (Haeckel 1834-1919).

tension plays an important role, since radiolarians in ocean conditions aim at a maximum overall size, investing the least amount of material possible in constructing their silicon skeletons.

The skeletal part supports the cell body of the radiolarian and protects the central



2. Multi-layered skeleton responding to impact forces and distributed loads (left drawing: Haeckel 1887) and cell body acting like a mould.

capsule. The skeleton provides the organism with a relatively large volume to protect it against predators. In order to reduce the energy needed to move in the water, the density of the complete organism is optimized to be approximately the same as the density of the water surrounding it. This implicates the importance of the dimensions of their body which needs to be as big as possible while keeping the weight relatively low. Since the sphere has the smallest surface area among all surfaces enclosing a given volume, this shape occurs frequently in the numerous revealed types of radiolarians. Radiolarians are able to control their movement in vertical directions. During ascent, the resistance of the liquid should be reduced, while it should be increased during descent to slow the fall. This explains the origin of the polar asymmetry, e.g. the bell shaped forms of some radiolarian skeletons, which act like parachutes.

Distribution of surface energy leads the siliceous particles into the grooves which separate the bubble-like vacuoles of the ectoplasm of the cell body (Figure 2). The result is the development of a delicate skeletal tissue composed of tiny rods arranged in a polygonal network.[1] Therefore, we can state that the tessellation of the shell tissue is defined by the way the vacuoles are arranged in the cell body, like a dynamic mould. In this way the skeleton is able to adapt to the cell properties, the inner spicule-shape, and the environment of the organism.[2]

The more dense parts of the skeletons serve to protect the central capsule of the cell body. They are produced in an early stage. It is often seen in skeletal tissue from earlier growth stadia, that the initially lighter tissue gets overgrown with tissue during the life span of the organism (+/-2 weeks).

Some reoccurring rules are noticeable while examining the skeletons of specific types of radiolarians which can be described as a silicon network of rods. The mutual tension between the rods tends to fashion them into a honeycomb. Mathematically, it is not possible to close a volume with hexagons. That is the reason why heptagons and pentagons occur incidentally, especially on curved parts[3]. When stronger rods come into play, it is also noticeable that weaker rods will attach perpendicular to the stiffer ones. During the growing process, rods will split repeatedly in two directions; therefore connections with more than three rods usually do not occur.

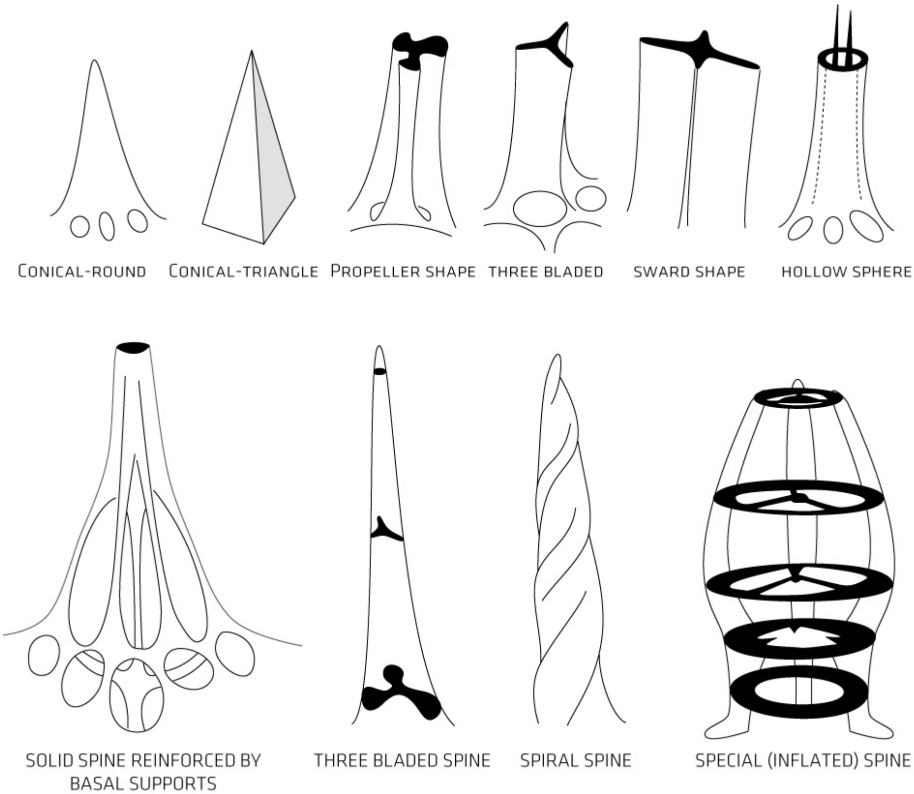
The spines are reinforced at their base, since they have to resist forces caused by movement or other impact forces from the environment. The spines are connected to the outer shell by a strong and stiff connection. A smaller section of the spines connects to the inner skeleton and they end up at the core of the skeleton; the primary sphere. The moment caused by the external forces on the spine, is counter acted by the shell(s). The inner parts of the spines could work as a transfer of the distributed loads to the different skeletal shells in order to distribute the loads evenly to the whole structure, and therefore keeping the internal stresses low and evenly distributed among the skeletal elements (Figure 2).

Spines may be hollow, with internal canals, or solid. They occur in various cross sections, sometimes developing different kinds of cross sections along their length (Figure 3). The bladed spines developed clear facets. The strength provided by such spines is the same as that provided by conical spines, but with less material. The spines consisting of three fused lamellae along one blade are most beneficial. The bladed spines often have a spiral twist.

Besides their aesthetic qualities, an interesting aspect of the tessellations of radiolarian shell structures is their growing process. During their lifespan, they grow in an emergent way, adapting all the time to unique and ever changing circumstances. In spite of this ability, their structures still result in bodies with similar qualities and appearances. Their homogenous skeletons are complex structures, based on a few basic rules, which make them able to evolve into a near infinite array of shell types. Depending on the sometimes scarce amount of available silica in their environment, radiolarian skeletons evolve shell tissues in a very efficient way.

Radiolarian-inspired structural geometry: the example of a parametric dome.

The principles described above are relevant and inspiring to both architects and structural engineers. The work presented here, follows this intent while focusing on the early phase of a structural design process, dealing with structural morphology. Re-interpreting the qualities of biological micro structures in a significant way for structural morphological investigations requires awareness of the similarities, but also of the



3. Diverse spine shapes of radiolarians (images based on: Afanasieva 2005).

relevant differences between these organisms and the built environment. This implies something beyond the mere application of radiolarian features to an architectural structure 10,000 times larger[4]. Since this research is meant as a design exploration using parametric design and genetic algorithms to investigate complex structures, the design criteria are kept simple in order to clearly identify problems and opportunities of the method.

Selection of investigated principles: the shape of a dome and its tessellation

From the preliminary investigations on radiolarians, three main levels of variations were identified: the overall shape of the organisms, their cellular configurations and the geometry of the spine. The first two are considered here under structural morphology. Concerning the overall shape, the principle of surface tension has been a very dominant factor in the evolution of radiolarians. This should be considered in the translation process into a macro structure, and the overall shape of the final model should be inherent to the logic of natural evolution. Therefore, this research has been limited to a semi-spherical dome shape. The choice of a fixed shape was due to a desired focus on the optimization of the surface tessellation.

The skeletal tessellations of radiolarians have been the focus of inspiration in

the proposed exploration.

Tessellation types were chosen after investigating several possible alternatives, including parametric hexagonal and other polygon-based tessellations. The Voronoi Diagram and Delaunay Triangulation have been selected to approach the aesthetic qualities and capricious appearance of radiolarian shells. By projecting points onto the architectural surface, the generated structure can be regulated in geometry and density, as the radiolarians base their skeletal tissue on the underlying cell substance. By manipulating the points, an infinite number of structural configurations can be found. The choice of how to organize the point distribution has a significant effect on the solution space of the parametric model. The way the points are projected onto the dome for this project, is structured by rings and regular point densities along each ring. This follows the fact that rings or ribs are typical structural elements of dome structures.

Genetics and the local environment of the radiolarians determine the manner of generation of their bodies. The genotype may change slightly each time the species reproduces, and new emergent properties are tested over and over based on whether the altered individual survives and passes on its traits or not. Using a combination of parametric modeling and genetic optimization, the ParEvO tool aims at leading the designer through a similar evolution process in a predefined way. This predefined digital model, having both fixed properties and variable parameters (genes) is central to the project. The criteria, which are integrated into the optimization part, make the designer able to search for optimal solutions within complex domains. The way criteria are defined, they offer the designer solutions in more than one direction. This approach to optimize a complex configuration is inspired by evolutionary principles and makes it possible for the designer to control the process in a systematic manner.

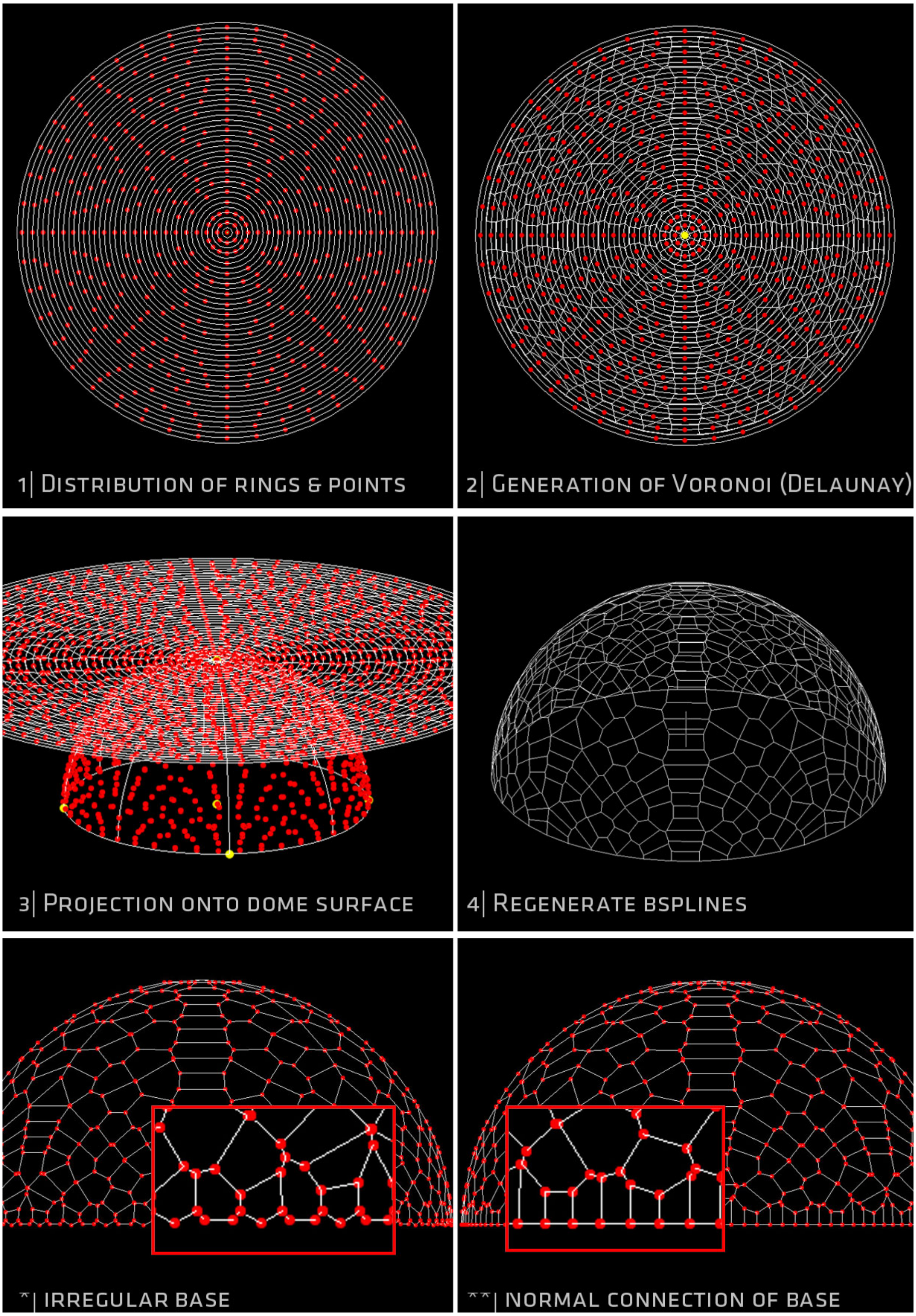
The comparison of two different types of dome tessellations, allows us to make some conclusions regarding which tessellation is more suited for dome structures in general. The evolved Voronoi version of the dome will be compared to the evolved Delaunay version of the dome structure. They are both based on the same system of distributed points. In this manner the relative merits of the two systems can be compared based on the chosen principles.

Parametric model

The previous section presented how the research on radiolarians helped to determine the actual setup of our dome model. Searching for a general logic to build the structure was necessary in order to approach the radiolarian skeleton structures and at the same time, enable the system to reconstruct itself in different ways based on different input parameters.

In order to define the solution space of the structure being explored in this project, a parametric model has been set up. The basic rules and variables, for the setup of the model, determine the direction in which the model is allowed to evolve. This characteristic allows us to control the evolution in a deliberate direction, which is useful, when testing specific hypothesizes. The degree of freedom can be controlled by defining a certain number of variables and rules in the parametric software and criteria in the optimization section.

Points are laid out on top of the dome shape according to a variable number of rings. The number of rings is variable and always evenly distributed along the surface of the dome. Along each of the rings, an even number of points are evenly distributed.



4. Procedure of dome setup in Generative Components.

The density of points along each ring is variable within certain limits. The bars defined by the Delaunay triangulation will automatically generate sets of "ribs" which will lead the vertical forces to the ground. Conceptually, all irregular ribs will work together as a network of ribs. The density of distributed points along the outer (lower) ring is always connected normal to the support plane, since forces are optimally distributed to a stiffer surface if the weaker parts are connected perpendicularly (as described in the first section).

As illustrated in Figure 4, points are distributed in the xy-plane using a GC script transaction. A plug-in called rcQhull is used to generate a Voronoi diagram or Delaunay triangulation based on the points. Subsequently, the points and lines are projected onto the dome. The geometry of the projection is constructed based on CR-tangent meshes and the south pole of the sphere is used as the center of the *inversive* transformation.[5] The parameters are comprised by variables and fixed conditions. The variables are: Number of rings: Rden (Range: 5, 7, 10, 20, 40); Number of points per ring: P (Range: varying from 4-121); Size of steel tubing (Range: 2"x2" to 20"x12"). Fixed parameters are: Dome shape: hemisphere; Dome radius: 50 feet; Members: steel tubing; Radial symmetry of structure: yes; Connection of points by: Voronoi and Delaunay. Based on this parametric model, the ParEvO method has been used as described in the following section.

The exploration concept

We call the exploration method developed and used in this paper ParEvO (parametric evolutionary optimization). It is different in focus from traditional optimization methods in that it is geared more toward allowing an exploration of a range of solutions rather than limiting the focus to one single 'best' solution. In traditional optimization, a single best solution is found for a given set of objectives applied to a specific problem. In the ParEvO method the goal is to expose a range of 'pretty good' solutions or "satisficing" solutions as they were called by the late Herbert Simon whose work spanned fields of artificial intelligence, cognitive psychology and computer science.[6] Following Simon's description of the act of design, it is often counterproductive to focus on one 'best' solution, because the objective criteria that produce it are usually incomplete. Particularly in the area of form determination, many criteria are not easily expressed numerically. However, when visually reviewing solutions, a trained designer has little trouble in making preferential selections even in ill-defined problems.

The ParEvO method combines both programmed objectives (such as least weight or number of members) along with subjective selections made by the designer. The designer can find a "satisficing" solution by sorting through the design space exposed by the ParEvO tool.**The ParEvO cycle**

Conceptually, the ParEvO cycle is fairly simple; however, the implementation is still in development. The version in this paper makes use of a lab of Windows PCs running in parallel and a web server, to run a series of both custom written and commercial software packages. The method has three basic components which form a cycle.

- Generation of variables (the GA)
- Generation of form (in GC)
- Analysis of form (using FEA)

The ‘genetic code’ of each solution as well as an image is maintained in a SQL database online. A web site provides access to one or a group of designers to view and sort through the solutions. Breeding can be set to run automatically in a continuous cycle based on defined objectives, or parents can be selected from the web page interactively by the designer. In either case, the parents are passed to a GA program where they are bred to yield a new child data set.

This child data is downloaded to a local PC running an associative parametric modeler (Generative Components by Bentley was used for this). The ‘genetic code’ for the child is then given form, and exported as a dxf file to a finite element analysis program to determine its performance.

STAAD-Pro was used for the analysis step. A VBA macro was used to complete the input data file including supports, member profiles and material assignments as well as loading conditions. The domes in this project were modeled with a projected, uniform, downward load of 40 PSF. STAAD-Pro was then used to design member sizes using standard steel tubing profiles. A variety of structural performance data can then be harvested from this step. For purposes of this paper we recorded the total weight and total member length as well and overall number of nodes and members in the structure.

Finally, the original list of code variables, plus the performance data along with an image of the geometry are uploaded to the server where they are entered into the database and displayed on the web page. Depending on the complexity of the problem, the process may continue to explore several 100 or several 1000 solutions. The examples used in this paper ran approximately 500 iterations each. Because the data needed to describe any solution are actually minimal, there is no problem in retaining all of the solutions in the database. Also, in the GA breeding there is a function that avoids duplicate solutions. During breeding, the database is checked and if the same solution has already been produced a different one is sought. Also, because the solutions are maintained in a database, a variety of searches can be made after the problem has run to explore the solution space.

Results

All of the generated domes are visualized via a web interface. The integrated sort feature makes it possible for the designer to analyze the population in different directions. The domes can be sorted twice successively based on: each variable defined in the parametric model, weight, number of members, number of nodes, total length of members and id tag.

In order to analyze some results and show the possibilities, we have chosen to sort the population first on the “Rden” variable and then successively by the weight of the structure. A selection from the generated population is shown in Figure 5.

As part of the ParEvO cycle, STAAD-Pro input files are generated for each dome. The STAAD files are retained and can be subsequently used for deeper analysis of any specific dome by the designer or a structural engineer. The files are collected and stored on the server, and can be downloaded via the previously mentioned web interface.

The lightest dome revealed by the ParEvO tool used the Voronoi tessellation with a ring density of 5, while the heaviest dome used the Delaunay triangulation with a ring density of 40. What is evident from these results is that the Delaunay dome seems to be structurally more efficient while being consistently heavier than the Voronoi version. The domes with high discrepancies in densities per ring are less efficient than configurations which are more evenly distributed. An abundance of ribs in one specific area of the dome will cause the structure to become excessively heavy.

A pair of the 7-ringed domes with similar weights representing the Voronoi and Delaunay geometries was selected for further analysis using STAAD-Pro (Figure 6 and Figure 7). It is evident that the geometry of the Delaunay dome is more stable and the structure seems more efficient since the torsional stresses, deflection and bending moments in the structural members is significantly lower than in the Voronoi dome. Another analysis was performed on two structures which were generated based on the same point set. Again, the Delaunay dome continues to outdo the performance of the Voronoi dome. Notable is the difference in weight. The Delaunay dome turns out to be more than four tons heavier in this case. One of the explanations for this phenomenon is that the Voronoi diagram covers a spherical surface more efficiently than a Delaunay triangulation allows. What also has to be taken into account is the way the forces are applied, as more thoroughly explained in next paragraph.

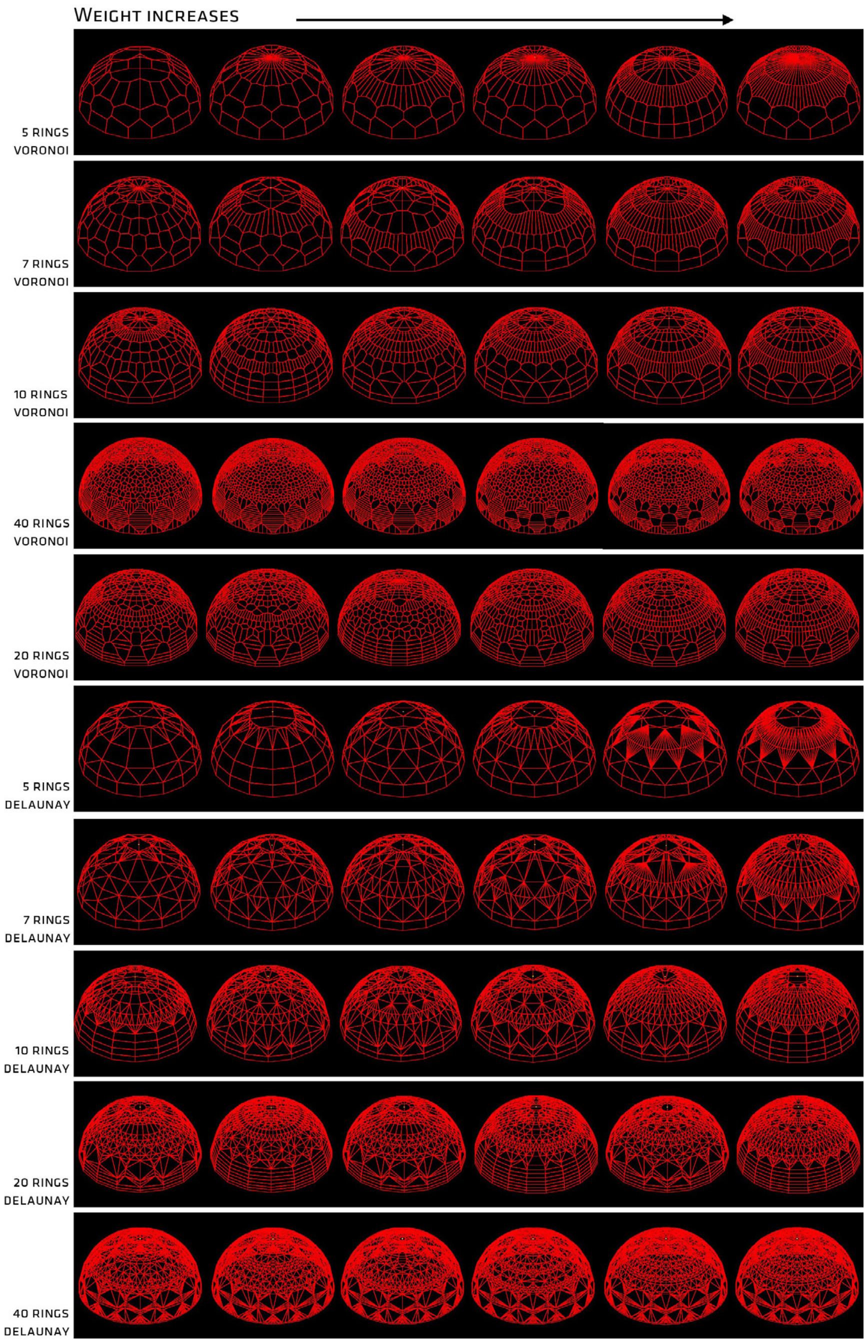
Although brief, these analyses show us that the Voronoi tessellation is optimal in covering a surface, using the least amount of material, but for structural purposes on architectural scale the Delaunay diagram turns out to be better in dealing with stability issues and the self weight of the structure.

Limitations and Simplifications

Although the goal of the exploration was to cover as much of the solution space as possible with the search process, practical aspects of programming the model limited the possibilities or the accuracy of the search in some ways. In modeling the geometry in Generative Components, We decided to limit the model to a relatively simple dome structure. Further levels of complexity can be added both at the overall shape level in order to investigate possible mesh variations, and at the structural level, including double layer space frames. Several parametric models have been built integrating both aspects and are meant to be further developed. However the current system encounters difficulties in quickly generating variations once the model reaches a certain level of complexity.

The structural analysis as it was performed also limited and directed the search in certain ways. One significant aspect in the finite element analysis that impacted form was the loading condition used. Normally, in the analysis of a structural system, several loadings and load combinations are considered. These include symmetric as well as asymmetric loadings. For a radial design the asymmetric loadings (such as ½ snow loads or directional wind loads) need to be considered to act in any direction. This is possible to do in the ParEvO method, but adds considerably to the computational time as well as the programming effort. Therefore, the loading was simplified to a uniform projected load of 40 PSF. Also, because the emphasis in the design was on the structural frame, added stiffness of infill panels was not considered. But this presents a problem in the STAAD analysis in that there is no element present (like a plate) to distribute the load to the members. To give an approximate load distribution to the members, the total load was calculated based on the projected area and then evenly distributed along the length of the members. This gives the correct total load but does not make a distinction as to the differential size of the cells.

Nonetheless, this paper is effective at demonstrating the procedural method and potential application to design of the ParEvO technique. Future research efforts



5. Selection of generated domes. Sorted by ring density and successively by weight of the structure.

will continue to refine the simulation techniques so as to more closely model true environmental conditions and thus enhance the ability to discover better responding forms.

Conclusion and Future use

The proposed approach uses ParEvO as a design tool to explore predefined parametric solutions. The example uses structural criteria while searching for an optimal solution. According to that, the ParEvO tool can be of value in the decision making process when dealing with design complexity, such as complex geometries, using computational tools. The basic generation of configurations can be helpful to explore the solution space of a specific parametric model. The genetic optimization component can be directed by the designer to allow the geometry to evolve in a certain direction, using structural performance as secondary input. The designer has complete freedom to manipulate the evolution of results, and is at the same time in control over the design process. Analyzing the ranked results helped students becoming more familiar with structural behavior of complex structures, and is meant to support designers without being too restrictive from the perspective of design. Applications of this tool are also envisaged with make use of other performance criteria such as solar performance, ventilation or acoustic behavior.

Acknowledgements

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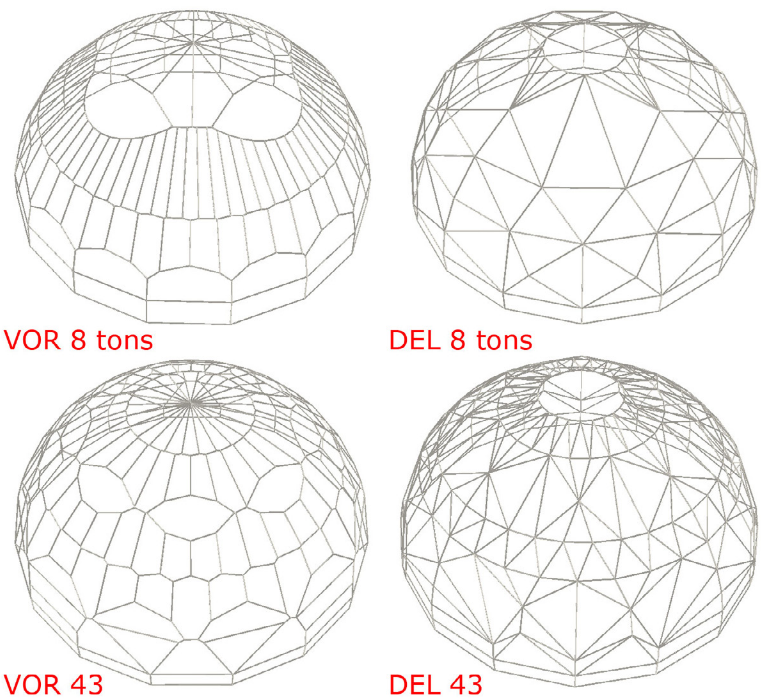
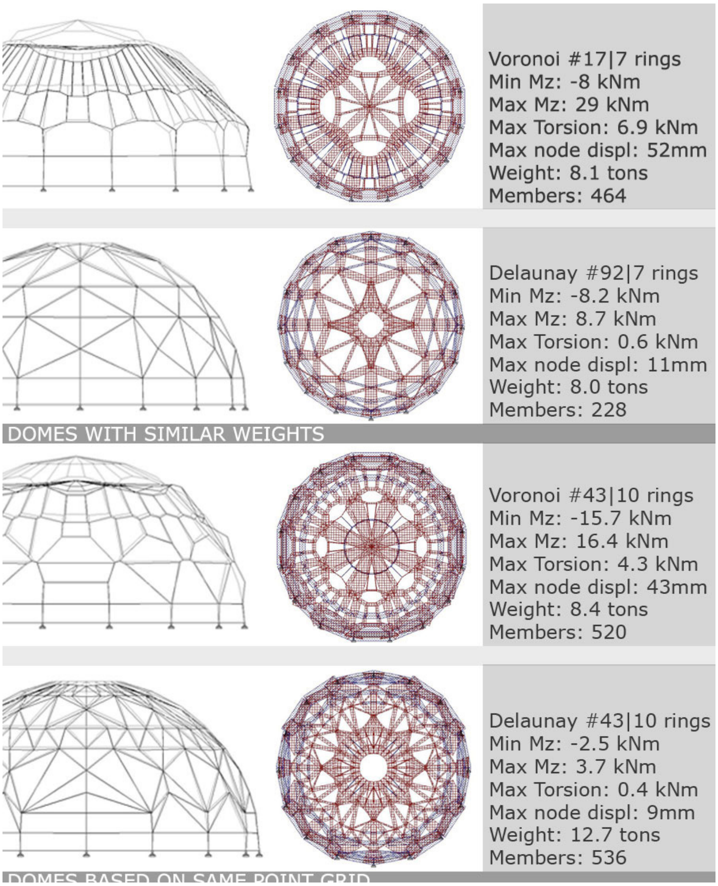


6. Analyzed dome configurations.



7. Voronoi dome versus Delaunay dome, analyzed in STAAD-Pro.Jeremy Perrault.

Hydra Lab, University of Michigan
We would like to thank also M. Arch Robert Cervellione, for the support given to the authors in using the rcQhull plug-in he developed.
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Endnotes

1 D'Arcy Thompson, *On Growth and Form* (New York: Cambridge University Press, 1961 (1917)).

2 M.S. Afanasieva, *Radiolarian Skeleton: morphology of spines, internal framework, and primary sphere* (Moscow: Pateontological Institute, RAS, 2005).

3 This is based on a personal conversation with Jaap Kaandorp, researcher in Computational Science at the University of Amsterdam.

4 The ratio of a linear dimension to its volume can be written by the general equation $V = L^3$. This implies that to enlarge a radiolarian to the size of a ten meter high pavilion, the length needs to be multiplied by a factor of 10,000. This will result in a volume of $1 \cdot 10^{12}$ times bigger than the original volume. Completely different forces have to be taken into account since gravity exerts a force which is proportional to the mass, and therefore to the volume of a body. The stresses *per unit area* in the construction will increase in the ratio as well when the volume gets bigger.

5 Reinaldo Togores and César Otero, *Planar Subdivisions by Radical Axes Applied to* Structural Morpholog (New York: Springer Berlin / Heidelberg, 2003) and Togores and Otero, *Computational Geometry and Spatial Meshes* (New York: Springer Berlin / Heidelberg, 2002).

6 Herbert A. Simon, *The Sciences of the Artificial* (Cambridge: The MIT Press, 1969).

Image Notes

1. Various tessellations of radiolarian skeletons (Haeckel 1834-1919).

2. Multi-layered skeleton responding to impact forces and distributed loads (left drawing: Haeckel 1887) and cell body acting like a mould.

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4. Procedure of dome setup in Generative Components.

5. Selection of generated domes. Sorted by ring density and successively by weight of the structure.

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7. Voronoi dome versus Delaunay dome, analyzed in STAAD-Pro.