ARCHITECTURAL DNA: A genetic exploration of complex structures

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Abstract

The approach demonstrated in this paper uses 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 visually exposes for the designer a range of good performing solutions within the design space. The application of the GA is combined with parametric software, in this case Generative Components (GC). The program described here as ParaGen (Parametric Genetic Algorithm), uses a Finite Element Analysis (FEA) 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 topologies based on radiolarian skeletons. The design procedure described includes user interaction in the exploration of solutions that perform well both for the explicitly defined programmatic criteria (structural) as well as for the implicit criteria provided by the designer (visual aesthetic).

Keywords: *structural morphology, parametric design, genetic algorithm, structural optimization.*

1. INTRODUCTION

Architectural discipline embeds complex processes of ideation and evaluation. Focusing on geometry, with recent advances in software and technologies, complex geometries and structures are becoming ever more possible for architects and engineers to explore. In nature we are confronted with the most intriguing and optimized examples of efficient structures every day. But it is not only beauty that we experience in natural systems. Their multi functionality appears in many cases to be the result of complex emergent systems. Although offering meaningful design models, it is hard for a human mind to comprehend this organized complexity, 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 through the design of a dome structure, inspired by the characteristics of radiolarian skeletons.

In order to explore the structural morphology of a dome structure, natural structures have been taken as inspiration in configuring the parametric geometry. Computational geometry techniques and genetic algorithms are used to support its exploration. We intend to present here the dual aspects of the work, regarding its contribution to architectural design activities in research and practice. This contribution is proposed as an example of a method of processing complex geometrical input, 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 investigation and evaluation of complex design alternatives.

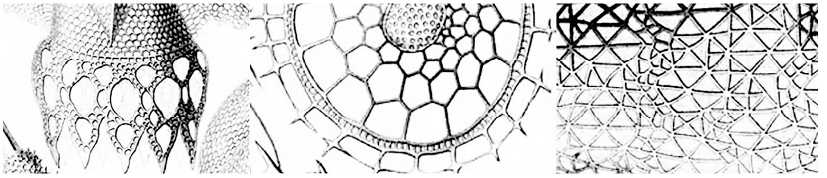
The integration of the discussed exploration method will provide the designer with a user friendly web interface where different solutions can be compared leading to a set of options which inform the ultimate design proposal. This procedure allows the designer to fluently proceed into the next design phase. In this way an interaction is achieved between computational expertise and design sensitivity, implementing computational geometry techniques (parametric software) and genetic algorithms into the creative process of the particular designer.

The first section of this work presents a short summary of the broad preliminary investigations which were carried out concerning the geometrical principles and material composition of radiolarian skeletons. 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 ParaGen method. Following this, the parametric model is described in detail and the optimization method is presented. Results are discussed, and developed one step further in order to show the value of this exploration procedure within architecture practice. Lastly, we will discuss genetic optimization as a design approach and critically evaluate the described computational method.

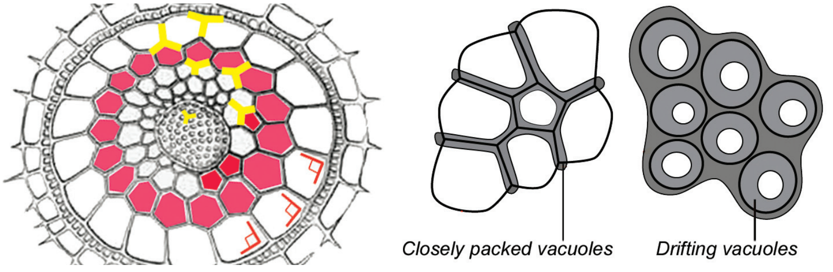
◀ Figure 1: A vision for the project.

2. RADIOLARIANS' STRUCTURES: SUMMARY OF INVESTIGATIONS

Focusing on the unicellular species of radiolarians, it is apparent that in spite of their comparative simplicity and minuteness, radiolarian skeletons exhibit extraordinary delicacy. Their lightness seems to show a 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-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 (figure 2).



► Figure 2. Various tessellations of radiolarian skeletons [2].



► Figure 3. Left: Geometrical characteristics of radiolarian skeletons. Right: Formation of radiolarian skeletons [1].

Since the sphere has the smallest surface area among all surfaces enclosing a given volume, this shape occurs frequently in the numerous known types of radiolarians.

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 3). 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 [3].

Some reoccurring rules are noticeable while examining the skeletons of specific types of radiolarians which can be described as a network of silicon rods (figure 3). 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. 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.

During their lifespan, radiolaria 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.

3. DESIGN PRINCIPLES

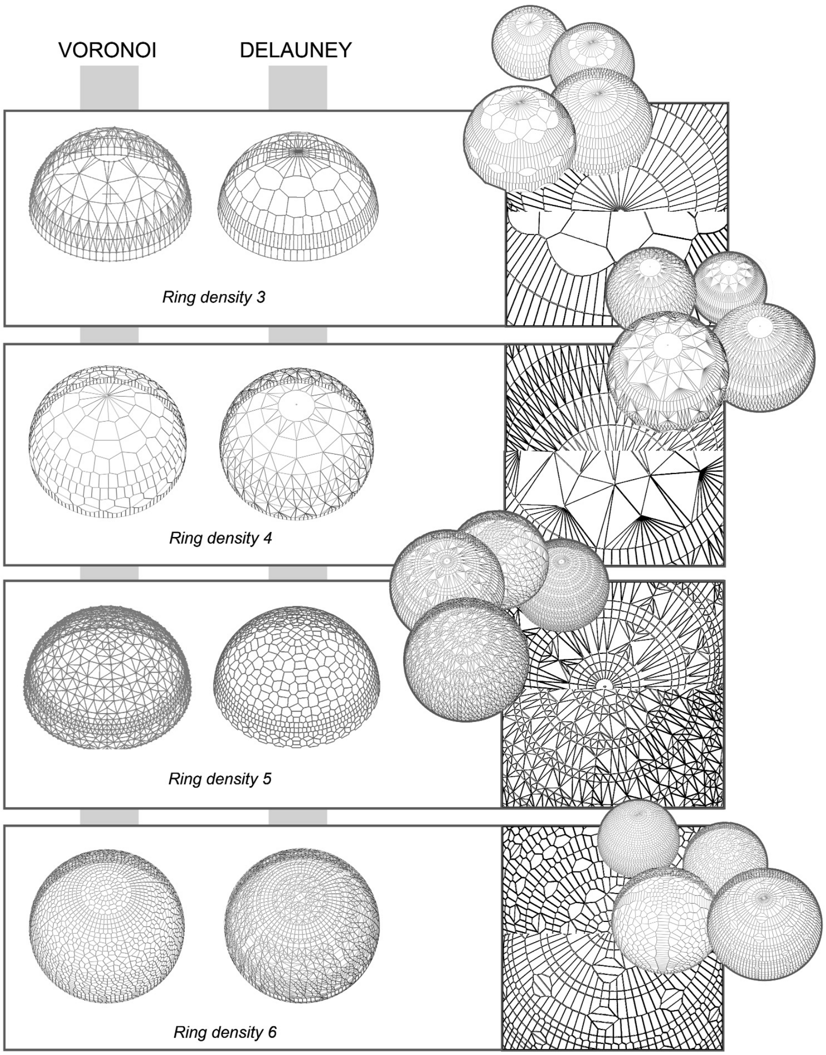
From the preliminary investigations on radiolarians, three main levels of variations were identified: the overall shape of the organisms, their cellular configurations and the geometry of the spine. A deeper description of the investigations done on radiolarian principles and the initial case study based on those principles is out of the scope of this paper. More detailed explanations can be found in a previous publication by the authors [4]. The research that has been done 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.

Therefore, the research was 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. 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 concentric rings and regular point densities along each ring. This follows the fact that rings or ribs are typical structural elements of dome structures. The tessellation of the structure itself, was initially based on the principles of the Voronoi and the Delaunay diagram. The comparison of two different types of dome tessellations, made it possible to make some conclusions regarding which tessellation is more suited for dome structures in general. An evolved Voronoi version of the dome has been compared to an evolved Delaunay version of the dome structure.

In order to approximate a natural evolutionary process in a controlled and systematic manner, both parametric modeling and genetic optimization are used as tools to explore the geometry of the dome structure. In order to execute this, the ParaGen tool is implemented in the exploration process.

ParaGen, as further described in chapter 5, aims at leading the designer through an evolution process in a predefined way. This predefined digital model, having both fixed properties and variable parameters (genes) is central to the actual significance of 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 in which criteria are defined, offers the designer solutions in multiple directions.

► Figure 4. Examples of parametric instances of Voronoi diagram based and Delaunay triangulation based domes.



The comparison between Voronoi and Delaunay solutions has shown in previous work, that Voronoi tessellation is better performing 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. However, on the basis of the aesthetics of the generated individuals, the Voronoi option was chosen for further investigations. The next chapters of this paper will focus on further analyses and optimization processes which have been run in an explorative way within the Voronoi domain. The parametric model and the ParaGen system will be described in the following according to their key aspects. A more detailed description of the work developed in the previous phase can be found in a previous publication by the authors [4].

4. PARAMETRIC MODEL - GENERATIVE COMPONENTS

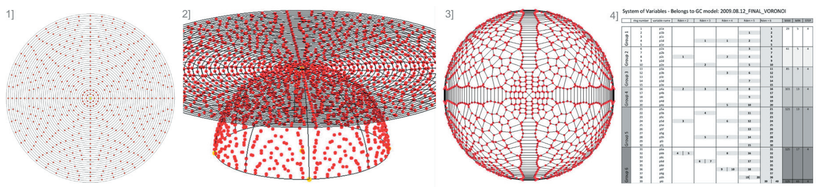
In order to define the solution space of the structure being explored in this project, a parametric model has been set up in Generative Components. The basic rules and variables, for the setup of the model, determine the directions in which the model is allowed to evolve. This characteristic allows us to control the evolution in deliberate directions, 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.

The geometry of the dome is controlled through a set of 40 variables (figure 5-4). Points are initially generated in a 2-dimensional configuration. The points are evenly distributed on a number of concentric rings on the xy-plane using a GC script transaction. The script recalls the 40 variables to define different configurations of the point set. The first variable, hereby called Rden, controls the number of the rings based on a set of if conditions. The number of rings can range from 4 up to 40. The other 39 variables are entirely or partially used to determine the number of points to be distributed on each of the selected rings, ranging from 5 to 125 points per ring. The output of the script is a variable set of points as shown in figure 5-1.

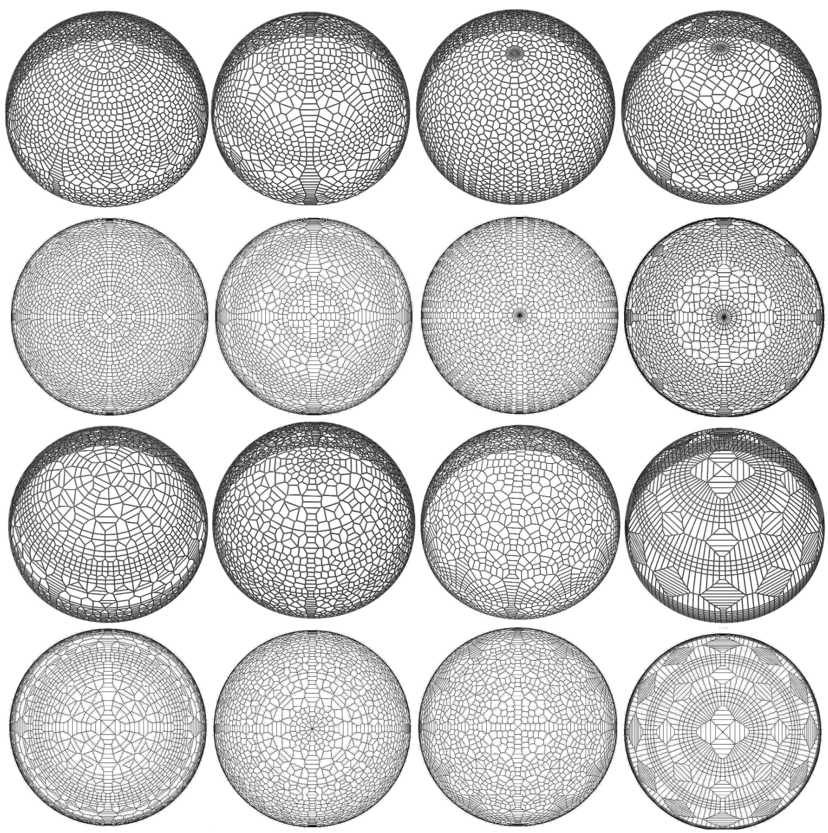
A plug-in called rcQhull is used to generate a Voronoi diagram or Delaunay triangulation based on the points. Subsequently, the points and lines are projected onto the surface of the dome. The geometry of the projection is constructed based on CR-tangent meshes and the south pole of the sphere is used as the center of the inversive transformation [5]. Figure 5-2 and 5-3 show the projection onto the dome shape and the final model of the dome.

Conceptually, all irregular ribs will work together as a network of ribs, a few manually set-up possible dome configurations based on those set of variables are shown in Figure 6.

In addition, other conditions and variables concerning the analysis (member properties and loading) were used in the FEA of STAAD-Pro. These included the members being selected based on US standard schedule 40 steel pipes and a uniform projected load of 40 psf (2 kN/m2). Based on the parametric model in GC, the ParaGen method has been used as described in the following section.



► Figure 5. Parametric geometry of the domes and set of independent parameters based on which the different instances of the model are generated.

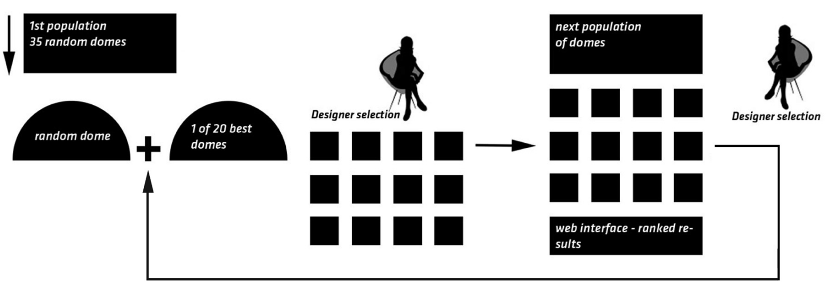


► Figure 6. Examples of eight instances of the Voronoi diagram based dome.

5. THE EXPLORATION CONCEPT IN GENERAL

For the work presented in this paper, an exploration method named ParaGen was used, which is based on a parametric design tool using genetic algorithms. It supports the exploration of form based on performance criteria. Despite the fact that it uses optimization techniques, it is different from traditional optimization methods which commonly focus on one 'best' solution only based on a given set of performance criteria. ParaGen instead provides for the exploration of a range of solutions. In the ParaGen method, the goal is to expose a range of 'pretty good' solutions that can be compared with one another. The visually oriented approach of the ParaGen method offers several advantages which can aid the designer in finding an appropriate solution. 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. Also being able to compare solutions side by side quickly highlights the differences in form which may be critical to the design intent. Finally, having performance data available with the images allows the designer to make informed judgments in choosing which direction to pursue.

The ParaGen tool combines both programmed objectives (such as least weight or number of members) along with subjective selections made by the designer. The designer can find good solutions by visually sorting through the current population of solutions. By selecting new parents from the population, it is possible to breed other similar solutions with the GA component of the tool. The GA program in ParaGen allows new solutions to be generated either by breeding two parents, or by mutating one parent. It is also possible to generate a complete random set of data to generate a new solution without any parents.



6. THE PARAGEN METHOD AND ITS APPLICATION TO THE CASE STUDY

Conceptually, the ParaGen cycle is fairly simple; however, the implementation is still in development. The version discussed in this paper makes use of a lab of PC's using Windows XP 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:

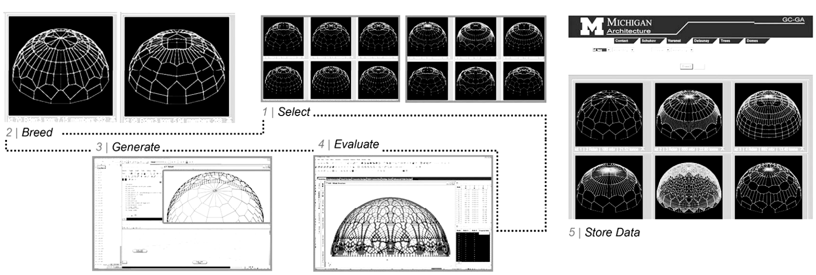
- Combination of variables (the GA)
- Generation of form (in GC)
- Analysis of form (using FEA STAAD-Pro)

This cycle is repeated a number of times for the case study as discussed in the following chapter.

6.1. The cycle

Each individual solution is run through the same ParaGen cycle to determine the specific geometry and performance characteristics. But the input data for GC, the genetic code of the solution is generated in different ways depending on the phase of the overall design cycle. Initially, the genetic code of variables is randomly generated on the server and downloaded to a local PC as an Excel file for processing by GC. This produces a start population. As each geometry is established in GC, the solution is processed through the rest of the ParaGen cycle. In this case study the performance analysis was carried out using STAAD-Pro (FEA) to determine structural characteristics associated with each solution. Member sizes can be designed at this point so weight and efficiency data can also be harvested (figure 11).

At the conclusion of the local part of the cycle, the original set of variables along with data files useful in a more detailed assessment of a particular solution (jpg, dxf, wrl formats of the geometry and the STAAD data file) are uploaded to the web server. The variables are maintained in a SQL database and linked to the data files so that they can all be retrieved by the designer through the web interface.



► Figure 7. The Paragen cycle.

After an initial random population is established, new parents are selected, and are passed to the GA program where they are bred to yield a new child data set based on crossing combination of the variables. The child data is downloaded to the local PC running the associative parametric modeler and the loop starts again. Depending on the complexity of the problem, the process may continue to explore several 100 or several 1000 solutions.

Two important aspects of the Paragen cycle are the visualization and exploration of the generated solutions, and the way the parents are selected which gives the designer the ability to interact with the process. With the 'genetic code' of each solution together with an image is stored in the SQL database, all of the generated domes can be visualized via a web interface. The integrated sort feature makes it possible for the designer to analyze the population in different directions for any variables or performance values. The solutions can be sorted and/or filtered based on: each variable defined in the parametric model, and the other performance values. In addition support files such as dxf, std, csv, wrl, and jpeg files, can be downloaded from the web page. Furthermore the website not only allows the designer to view and sort through the generated solutions, but it also provides access for the designer to select specifically desired parents. The selection of the parents can in fact happen in two different ways. Breeding can be set to run automatically in a continuous cycle based on defined objectives; or parents can be selected by the designer. In the second case, the selection occurs interactively from the web page.

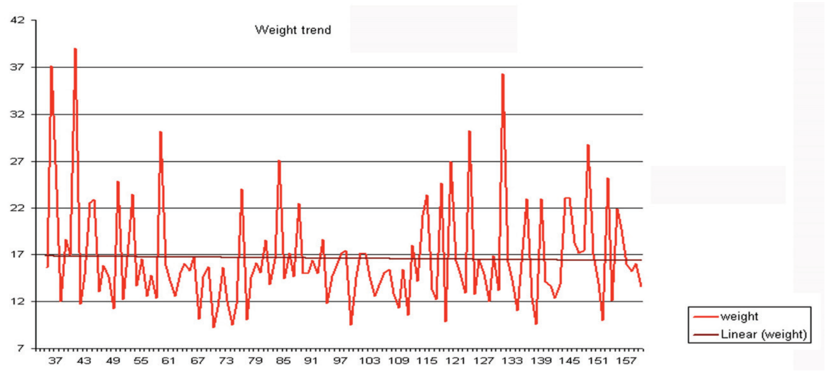
6.2. Phase 1: First population of random domes

Having a completely defined GC model of a dome structure as a starting point, the first population of random domes is generated by the ParaGen tool. The GA section of ParaGen, assembled 35, different combinations of the 42 variables per dome. The size of this initial population is based on the complexity of the problem. The limited number of 35 domes will illustrate the process sufficiently for this test case. The FEA-part of ParaGen imports the dxf file of each dome into Staad-Pro, applies loads, materials and supports to the model and runs a Finite Elements Analysis. The output information is in this case the weight, the number of members, the number of nodes and the total length of members. These are labeled for each specific dome together with the data from GC, which is a list of all variables, an id tag and id tags of the potential parents. Via the web interface, the first generation of randomly created domes is viewable. The designer can sort the published domes based on all variables twice successively, in order to explore trends, possibilities and properties for all different dome configurations.

6.3. Phase 2: Propagation of the first population

In order to explore and direct successive populations toward a chosen status, ParaGen was set in the second phase, to select parents from two groups. The first parent is randomly selected from a group of the most fit solutions, and the second parent is selected from a larger group of recent solutions. For this case study, the number of best individuals was set to 30, and a second population to 125 domes. Using the values stored in the SQL database it is possible to analyze all generated data in Excel to visualize trends and properties of the generation of domes based on input variables and performance values. As illustrated in Figure 8, the weight starts to converge slowly towards a minimum in this phase. The larger the initial population is, the clearer this convergence will be, depending on the set number of top ranked domes in ParaGen. Investigating the dome population until this point, it appears that mainly two strategies have been developed by ParaGen in meeting the objective function (fitness).

Another strategy seems to be lightness of the dome. The domes with large members, less rings and therefore the least number of members scored best. Another successful strategy seems to be create a surface tessellation which is as dense as possible with horizontal beams in the lower area of the dome. Since the steel tube size in the FEA software is limited to a minimum of 21 mm diameter, this strategy is limited by the structural optimization. The first strategy is not limited because there is no maximum steel pipe size.



► Figure 8. Weight trend of the second population.

6.4. Phase 3: Decision on further breeding strategy

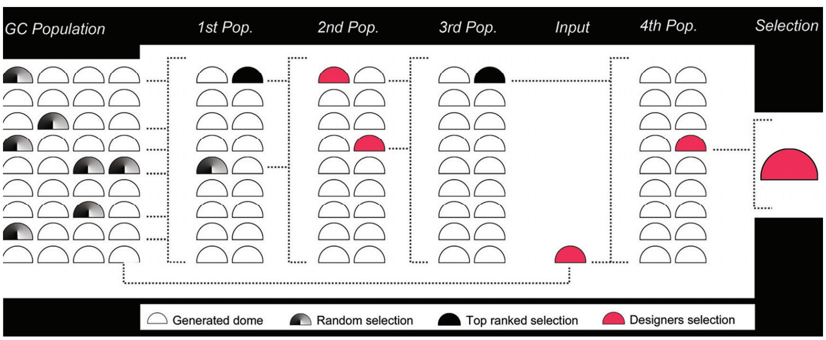
After investigating the domes of the first and second population, the designer can choose to either breed two specific individuals from the first generation of domes, breed one selected dome with the top ranked population, or breed 2 random individuals out of the best performing range. For this test case two specific domes out of the best performing range have been chosen, both with different characteristics, a certain level of aesthetics and the same number of rings. A third population was generated, based on the variable sets of those specific domes.

6.5. Phase 4: Intervention of Designer

Investigating this third generation, the designer has been able to learn and evolve a population of forms toward a certain direction. If the results are not satisfactory or the population converges in an unwanted direction, the designer can intervene, by either choosing and crossing different individuals from the existing population, or inserting a new self designed instance straight from GC and crossing it with the best out of the existing generation. The latter is done for this test case. This intervention was successful in the sense that it positively influenced the geometrical qualities of the domes, without losing the more efficient structural set-up in most cases (figure 10).

6.6. Phase 5: Selection and Proceedings

The designer can choose to proceed with the evolution process until it leads to a satisfying result. If the designer has chosen a specific individual for further development, data files can also be retrieved from the server. As part of the ParaGen cycle, STAAD-Pro input files, as well as dxf files and csv files are generated for each dome. The STAAD-Pro 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. A diagram of the previously described selection process is shown in Figure 9.



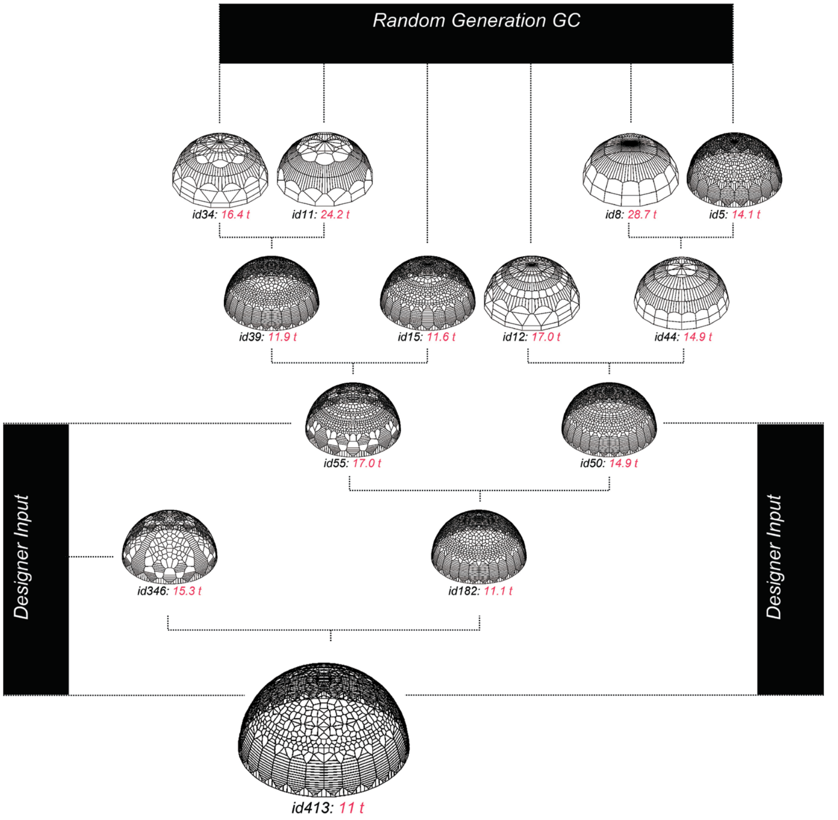
◀ Figure 9. Schematic view of the dome populations.

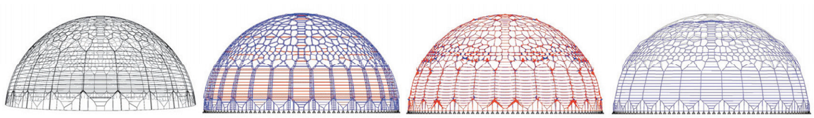
7. LIMITATIONS AND SIMPLIFICATIONS

The example used in this paper ran approximately 800 iterations. 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 emphasizing different parameters.

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 for further development. However the current system encounters difficulties in quickly generating variations once the model reaches a certain level of complexity. This is the main reason the ParaGen method has been designed to operate in a parallel environment. Any number of machines can be quickly added to the cluster simply by connecting to the website and downloading the input data set for GC.

► Figure 10. Genealogy tree of the final dome (dome 413).





◀ Figure 11. Images from the structural analysis of the final dome (dome 413).

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 snow loads or directional wind loads) need to be considered to act in any direction. This is possible to do in the ParaGen 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 (2 kN/m2). Also, because the emphasis in the design was on the structural frame, added stiffness of infill panels was not considered. 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 ParaGen technique. Future research efforts 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.

8. CONCLUSION & FUTURE USE

The proposed approach uses ParaGen as a design tool to explore predefined parametric solutions based on a combination of visual and performance rated criteria. The example uses structural criteria and material efficiency to provide a pallet of good solutions. In this way, the ParaGen tool can be of value in the decision making process when dealing with design complexity, such as complex geometries generated with computational tools. The genetic optimization component of the tool can be directed by the designer to allow the geometry to evolve in a certain direction, using structural performance as secondary criteria. The designer is invited to interact in the genetic selection, and thereby influence the outcome of the design process. The interactive process can help to inform the design process and allow the designer to become familiar with structural behavior of complex structures. ParaGen is meant to support designers without being too restrictive from the perspective of design. Applications of this tool are also envisaged to make use of other performance criteria such as solar performance, ventilation or acoustic behavior.

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