Structural morphologies and sun transmittance control: integrated parametric design using genetic algorithms

M. Turrin  
*Faculty of Architecture, Delft University of Technology, Netherlands*

P. von Buelow  
*Taubman College, University of Michigan, USA*

R. Stouffs  
*Faculty of Architecture, Delft University of Technology, Netherlands*

Abstract

In this paper we discuss the support provided by parametric modeling and genetic algorithms to performance oriented design processes; the topic is discussed and exemplified with specific reference to modular wide span roofs. First, the paper introduces the concept of performance oriented design and describes potentials and limits of parametric modeling in supporting the process. Among the potentials, parametric modeling enables the designer to automatically generate alternative design solutions; among the current limits, the difficulties to evaluate the generated alternatives are pointed out. A systematic performance oriented exploration of the solution space of the model is in fact mainly not possible due to the wide range of solutions. Based on their capability of guiding the generation of design solutions to fulfill a given set of performances, genetic algorithms are discussed to support the exploration. A system to integrate parametric modeling and genetic algorithms is then shown. The paper presents two examples developed by using this system. The first one deals with structural performances and concerns the structural morphology of a dome. The second one deals with solar energy transmission and concerns the solar heat gain and daylight transmittance of a roof.

*Keywords*: performance-oriented design, integral design, parametric modelling, genetic algorithms

1 Introduction

With specific reference to the case of modular wide span roofs, we discuss the support given by parametric modelling and genetic algorithms to performance oriented design. We relate the concept of performance oriented design to integral design as a way to approach the complexity of architectural processes. Complexity is inherent to architectural design and concerns the overall process through a network of interdisciplinary interrelations; integral design refers to the simultaneous integration of various and interdisciplinary aspects; performance oriented design directly relates to the concept of performative architecture, which searches for forms and materializations based on their performances. The detailed investigation of these three concepts is beyond the scope of this paper; however a brief introduction is given here which relates them to the specific topic of the paper.

According to Branko Kolarevic, performative architecture can be defined as *the one in which building performance, broadly understood, becomes a guiding design principle* (Kolarevic, 2003). When referring to architecture, the concept of performance embraces a wide range of different fields, involving both soft and hard issues. In a general sense, it includes technical aspects from structural to thermal, lighting and acoustics, aesthetics and perception, maintenance and economics; to name only
a few. Dealing with the mentioned performances and the interrelations through which these aspects affect each other is part of the design complexity.

When focusing on large roofs, aesthetics, structural performances and economics often dominate the design process. However, the current increase in attention to energy-related aspects, generates new challenges which require special attention. Particularly, the use of renewable energy resources needs to be confronted in the design. Based on this, structural morphology and solar energy transmittance have been selected here as key aspects. By focusing on these aspects, the paper discusses the support provided by the integration of parametric modelling and genetic algorithms, aiming at an integrated design in the early and conceptual phase of the process.

2 Parametric modelling and genetic algorithms as a support for performance oriented design.

This section presents the potentials of parametric modelling and genetic algorithms in supporting performance oriented design processes, favouring the early integration of different disciplines. Parametric modelling is first presented by discussing its potentials and limitations. Then, in relation to these, a genetic algorithm is introduced as a possible solution. As an example, the ParaGen design tool is presented which integrates the two techniques.

2.1 Potentials and limits of parametric modelling

Parametric modelling has the capability to represent both geometrical entities and their relationships. These relationships are structured in a hierarchical chain of dependencies, established during the preliminary parameterization process. The independent properties of the model are usually expressed through independent parameters, and their variations generate different configurations of the model. This gives parametric modelling the great potential to automatically support the generation of a large set of design alternatives. Presenting the parametric modelling techniques is out of the scope of this paper and further details on the subject can be found in other publications (i.e. Aish and Woodbury, 2007); while hereby, specific attention is given to the exploration of the generated design alternatives. The instances of the parametric model can in fact be explored with respect to a given set of design criteria. In order to make this process successful, the solution space of the model should be meaningful with respect to the criteria that are being analyzed. This mainly depends on the parameterization process, which requires consistent modelling of the design criteria. Particularly, in the context of a performance oriented design, a proper parameterization process allows instances to be generated that differentiate based on key performance aspects. A knowledge and expertise based approach is therefore required during the parameterization process, and is mainly based on interdisciplinary collaboration. Also, the solution space of the model needs to be adequately explored in order to identify suitable design solutions among the different alternatives. Due to the breadth of the solution space, its systematic exploration is not possible when left to the intuition of the designer. This is a definite drawback when using parametric techniques, and it becomes even more problematic when dealing with interdisciplinary aspects. The integration of other computational techniques, such as search techniques related to the analysis and evaluation of performances, is proposed here to solve this problem.

2.2 Potentials of genetic algorithms combined with parametric modelling

Genetic algorithms are cyclic search techniques which operate on generations of large sets of design solutions (populations). Operations including re-combination, mutation and selection progressively shift successive generations toward solutions which perform better when evaluated with respect to a given single or multiple criteria (fitness function). The similarity between the parametric generation of
instances and the genetic algorithm based creation of populations makes the combining parametric models with a genetic algorithm optimization a good fit. The combined techniques are well suited to address the creation of instances toward the one most fitted to the fitness function. The fact that the genetic algorithm has no knowledge of the fitness function allows the optimization cycle to be applied with respect to whatever performance is desired. This potential is at the base of the ParaGen method presented below.

2.3 ParaGen

The ParaGen exploration process is a design tool currently in development. By using a series of both custom written and commercial software packages, it constitutes a cycle which links three basic steps: the assignment of values to the parametric variables; the generation of the corresponding geometry; and the evaluation and selection of generated solutions based on performance. In the first step of the cycle, Genetic Algorithm (GA) routines are used to select and combine the values of the variables. In the second step of the cycle, parametric modelling software (e.g., Generative Components) is used to create different instances of a solution geometry based on the values supplied by the GA for the independent parameters. In the third step, the geometric solutions are evaluated using simulation software for the analysis (e.g., STAAD-Pro for structural performances, and Ecotect for solar energy evaluations). The ‘genetic code’ of each solution as well as an image of the defined geometry is maintained in a SQL database online. This database becomes and ever growing genetic pool of solutions which can be viewed and sorted by a designer or team of designers through a web interface. The web interface also allows the designers to interact with the process. Breeding can in fact 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 string is downloaded to a local PC running the associative parametric modeller that gives geometric form to the ‘genetic code’ and exports it to the analysis program to determine its performance.

3 Two case studies

Two examples based on the ParaGen tool are shown here. The first one was developed as a master student project tutored by the authors and focuses on structural morphology; the second one is currently used by the authors for an active exploration of solar gain control and day lighting for large modular structures.

3.1 Structural morphology: an example of a dome

In this example, the structural morphology of a dome was explored by taking natural structures as inspiration. The exercise was developed as a process of learning from nature, with reference to a meaningful selection of geometrical principles and the parameterization of the structural geometry. The form was based on a logic extracted from radiolarian structures. The generation of different instances was guided by the search for structural configurations with minimal weight and acceptable deflection.

More precisely, the structural geometry of the dome was modelled based on points distributed along coplanar rings. The parametric variables regulated the number of rings and the number of points per ring, thereby allowing the generation of design alternatives based on different densities and distributions of the points. For each configuration of the points, segments (representing the structural bars) were generated by following one of two principles: the first one used Voronoi diagrams and the second one Delaunay triangulations. Each Voronoi and Delaunay solution was projected onto the semispherical dome by following a construction based on CR-tangent meshes and using the south pole of the sphere as the center of the inversive transformation (R. Togores, C. Otero, 2002 and 2003).
As a result of this process, two series of respectively Voronoi and Delaunay based domes could be investigated by varying the independent parameters. Figure 1 shows some examples.

Figure 1. Examples of the steps of the process: a) distribution of points along the rings; b) generation of either Voronoi diagrams or Delaunay triangulation; c) projection onto the dome; d), e) examples of Voronoi and Delaunay structural solutions [image by Maria Vera Van Embden Andres].

For both Voronoi and Delaunay solutions, the ParaGen method used a finite element analysis to determine member forces under a simulated snow load. Individual members were then sized using steel pipe sections and the structural performance was measured by the total weight and stiffness of the form. The complete cycle of selection, recombination, and evaluation was used to optimize and explore a large range of solutions. Solutions that exemplify each of the two principles are compared in Figure 2. Further details concerning this process and results can be found in a previous publication (Van Embden Andres et al., 2010).

Figure 2. Example of comparison of Voronoi and Delaunay based solutions [image by Maria Vera Van Embden Andres].

3.2 Solar energy transmission: an example of a roof system

In this example, a large roof is explored with respect to thermal and daylight comfort of the spaces underneath. The roof is meant to cover an approximately 50x50 square meters area. It has a cladding system based on a combination of opaque and transparent glazed panels, and it is located in Milan, Italy. Due to the local climate, the covered area is subject to a risk of overheating in summer. The strategies for reducing this risk are various; among them, the example implements the use of ventilation for cooling on one side, and on the other side the control of the solar energy transmission through the roof. Based on the effect of the roof configuration on these aspects, three geometrical properties have been parameterized: the curvature of the roof, the dimensions of the cladding modules and the inclination of the glazed panels. The roof is modeled as a NURBS surface and tessellated with three-dimensional components representing the cladding modules. Each component is a combination of six pyramids each with triangular base, together forming a hexagonal element. Based on an algorithmic pattern, each face of the pyramids can be either an opaque or transparent glazed panel. Opaque panels are south oriented in order to reduce the direct solar radiation. Figure 3 shows the hexagonal component tessellating different design versions of the roof.
Three levels of independent parameters have been identified as meaningful variables: the Z Cartesian coordinates of the NURBS’ control points (regulating the curvature of the roof); the density of the tessellation pattern (regulating the dimensions of the tessellation modules) and the height of the pyramids (regulating the inclination of the glazed panels). The first aspect has a direct relation with the cooling air-flow; while the second and third ones mainly affect the solar energy transmission of the roof. Those two latter are the design aspects that have been selected to be explored through the optimization process, starting from the case of a flat roof configuration; Figure 4 shows some of their instances.

The described system is explored by searching for a solution that allows the maximum daylight transmission and the minimum solar heat transmission through the roof, in summertime; and the maximum daylight and solar heat transmission during wintertime.

4 Conclusions

Based on the use of the ParaGen tool, the proposed method supports the designer in exploring wide ranges of parametric design solutions. Particularly, it allows integrating in the early phase of the process the evaluation of various design performances. In the two examples that have been presented, structural and solar energy criteria have been used; however the structure of the tool allows making use of other performances as well. Its versatility for different design criteria is a first advantage that needs to be pointed out. Furthermore, the processes so far experienced made clear the importance of the active role of the designer during the process. This is a key aspect of the genetic optimization component of the tool. The designer can in fact direct this component to allow the geometry to evolve in a certain desired direction, using the performances as secondary input. With this respect, ParaGen demonstrated a relevant value in combining on one side the freedom in manipulating the direction toward which the results evolve and on the other side the optimization of the selected performances. The control given to the designer over the process is a key potential also when integrating the tool in teaching activities, since this aspect increases the chances to understand the relationships between the geometrical properties and the performances of the design solutions.
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References


