Optimization of structural form using a genetic algorithm to search associative parametric geometry

P. von Buelow
University of Michigan, Ann Arbor, USA

A. Falk
KTH School of Architecture, Stockholm, Sweden

M. Turrin
Delft University of Technology, Delft, The Netherlands

ABSTRACT: Different methods using evolutionary computation (EC) have been successfully applied to structural form optimization for many years. A well known limitation of these methods is the computational effort required to analyze significantly large and complex systems. As a result most examples have been limited to simple truss forms or smaller aspects of overall structural systems. This is because the number of variables used to describe the structural geometry limits the size and complexity of problems that can be explored using EC methods. One solution to this limitation is the use of associative parametric models. In recent years use of parametric modeling software has become more widespread in architectural design. Parametric approaches to geometric modeling have the advantage that they are able to describe large, complex systems with very few variables. The reduced number of variables needed to describe geometric systems makes parametric models ideal for use with EC to explore optimal forms. This paper shows examples of how large, complex structural systems can be optimized for basic parameters like weight and number of components by combining a genetic algorithm with a finite element analysis and parametric modeling software. The procedure is outlined with specific applications. Examples show the use of this technique used to explore complex spatial structures. Results are shown with specific documentation of computational effort required.

1 INTRODUCTION

1.1 *Modeling a multitude of aspects*

Development of technology and development of constructed form goes hand in hand. Many examples in history show visionary designs in mind-warping sketches of objects and structures, which failed to make the transfer into the physical world. As technology develops, the possibilities at hand multiply, and in some cases historic visions get realized first much later when technology makes them possible. For example the Leonardo bridge project, where a timber bridge design from 1502 by Leronardo da Vinci was finally built in 2001 in Aas, Norway. The bridge was originally to span the Golden Horn in Istanbul with 240 m; 500 years later the design has been realized with a 110 m span constructed with curved glulam beams. During recent years development of digital tools for design and modeling have developed in both areas of engineering and architecture. These tools simulate and analyze structural behavior and wind flow, generate free-form design, and predict the influence of material specific properties. A freedom of how and what to design has opened up and the representation of the designed object gets closer and closer the physical object itself.

The more complex the object and the tool get the more important it gets to direct and control the output: The model as a tool to do what? The model as a representation, but how simplified?

These questions are here approached by looking at performance-based design and aiming at integrating the architectural performance evaluations in the early phase of conceptual design and geometrical morphogenesis. During the conceptual design, geometrical shapes are explored with high level of simplification and abstraction, however their level of complexity is notably increased by the amount of performative information the shape embodies. Managing this complexity and controlling the output become crucial when considering that the choices made in the conceptual phase have a great impact on the final performances of the project.

In this paper we show a method which combines evolutionary computation and parametric modeling to support early phases of design with a tool that combines exploration with optimization. In this context, design and analysis must be treated at two different but tightly linked and intertwined activities. An act of optimizing by using computational tools does not have to result in one single solution presented from a black box, but may through evolving populations of solutions, allow for a number of versions of similar efficiency to be explored. This leaves the designer with a higher degree of freedom and creativity in the design process. Parametric modeling offers capacity to explore complex forms on both the architectural and the structural level. The performance of these forms can then be simulated with different combinations of analysis software. In this way the designer can follow an informed path to better solutions, rather than leaving the resulting product to chance encounters.

2 GENETIC SEARCH

2.1 *Traditional evolutionary based form optimization*

Evolutionary Computation (EC), also called Evolutionary Algorithms (EAs), are a class of stochastic numerical methods based on analogies with biological genetics. EC paradigms have been developed by different researchers starting in the late 1950's and early 1960's (Mitchell, 1996. p. 2). Methods which have found application in architecture and engineering include:

– Genetic Algorithms (GAs)
– Evolution Strategies (ESs)
– Interactive Evolutionary Computation (IEC)

Each of these methods uses generations of populations of solutions to search a design space for solutions which perform well when assessed against objective criteria. How well they perform is a measure of their fitness, and the population gradually evolves through breeding, mutation and selection toward the more fit solutions.

The individual solutions, which in this paper are structural, geometric forms, are described by variables. The variables are strung together into a "chromosome" which is operated on (breeding, mutation, selection) to find new, more fit individuals. The more variables needed to describe the geometry, the longer becomes the chromosome string. The population size is proportional to length of the chromosome and the number of generations needed to find convergence is a factor of both. All of this affects the level of computation required. In short, the more variables that are required to describe the geometry, the more computationally intensive the problem becomes (Goldberg, Deb & Clark 1991). Problems can easily run into thousands or 10's of thousands of solutions each requiring an analysis to determine fitness.

As a result the degree of structural complexity is limited by the number of variables needed to describe it and therefore the level of computational effort needed to find good solutions (in terms of days of run time).

2.2 *Parametric modeling*

In the context described above, parametric models offer a solution to the dilemma of too many variables. Parametric models are able to describe very complex geometric systems in relatively few variables and still allow a wide range of variation. In recent years software such as Generative Components (Bentley Systems), Grasshopper (Robert NcNeel), Digital Project (Gehry Technologies - Dassault Systemes) and others have made parametric modeling techniques readily available for architects and engineers. Figure 1 shows four variations of a single parametric model. However, as designers begin to explore the range of solutions reachable with parametric modeling, the problem becomes how to sort through the myriad of geometries to find the ones which are the better performers. For this task of searching, a genetic algorithm is well suited. And since the parametric model usually employs a relatively small number of variables, the two are a good match.

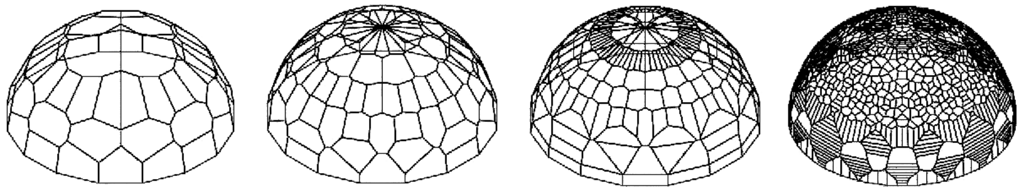

Figure 1. An example of a parametric structural system generated with Generative Components. (van Embden Andres, Turrin & von Buelow, 2009)

3 COMBINING PARAMETRIC MODELING WITH GENETIC SEARCH

3.1 *The ParaGen method*

The method presented in this paper is called the ParaGen method, and it is an example of a parametric design tool using genetic algorithms. The method takes advantage of commercial software for the parametric modeling and the analysis. In this paper we show examples using Generative Components (GC) for the parametric geometry generation and STAAD.Pro, a finite element analysis (FEA) package for the structural analysis. It is fully possible to substitute any other parametric modeler (for instance we have also used Digital Project) or any other digital simulation software for the analysis (for example Ecotect). The process is cyclic and is controlled by a program located on a web server. Any number of clients can attach to the web site and participate in the computation. This results in an "on the fly" parallel computing network. Figure 2 shows the ParaGen cycle.

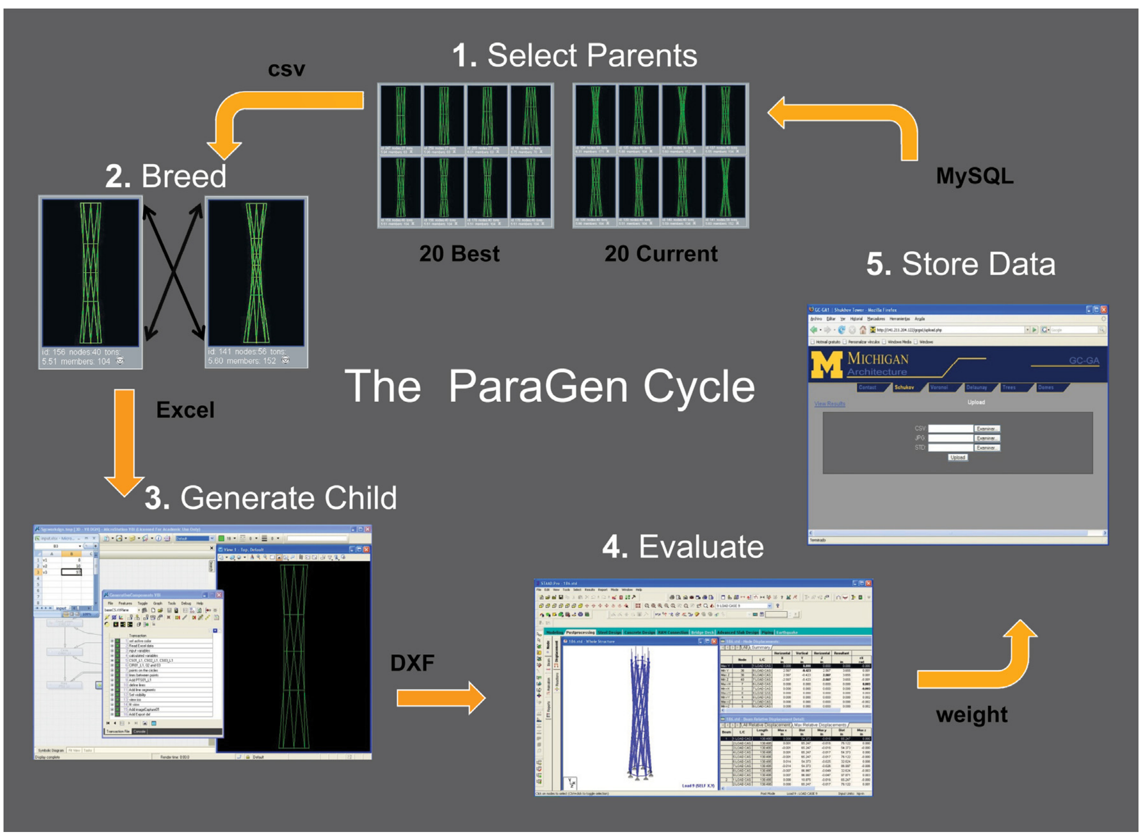

Figure 2. The five basic phases of the ParaGen cycle: select, breed, generate, evaluate, store data

3.2 *Post-exploration with the SQL database*

As the GA searches through the myriad of possible solutions, any desired parameters can be collected from the results of the analysis along with images and input data files for the software. All of this is uploaded to the web server. Here the data is entered for each solution into a SQL database and the images and files are stored for retrieval on request. Holding a few values from each solution in the database is not a problem even if the solutions reach tens of thousands. Database software is designed for just such storage and retrieval of large sets of data. The result is that after the run has completed, the solutions may be further explored and sorted by any of the variable parameters or analysis results. A double sort function is used on the web display so that the results can be sorted by first one parameter followed by a second, e.g. first by number of members followed by weight.

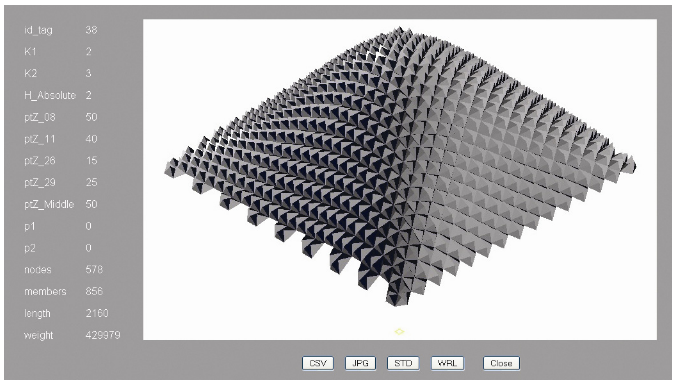

Figure 3. Viewing details and extracting information on any solution.

3.3 *Interactive exploration*

Generally, the method runs without human interaction until sufficient solutions are stored in the database to allow for exploration of the results. However, it is also possible for the user to select parents interactively using a web browser. By clicking the "breed" button without any selection a random solution is generated. If one solution is selected from the screen, then that individual is mutated to produce a new solution. And if two selections are made they are bred as parents to generate a child solution. Figure 4 shows this function. Also a full list of data can be retrieved for any individual along with enlarged and VRML depictions (Virtual Reality Modeling Language, which allows dynamic navigation through the 3D model). The VRML display is especially helpful for visualizing the larger complex geometries. Also since the VRML file is produced after the structural analysis, it can show calculated member sizes. Figure 4 shows an example of this output.

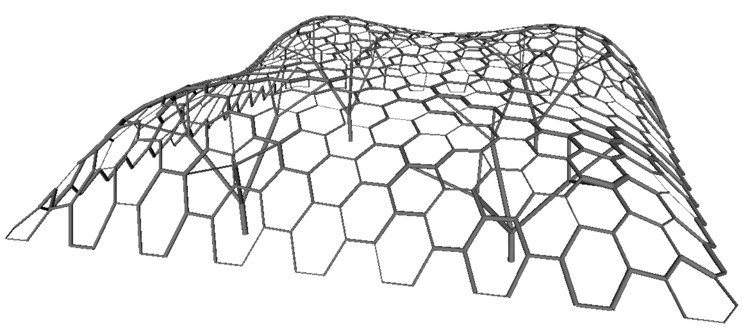

Figure 4. A VRML model used to depict the geometry. These models can be rotated and moved in 3D.

4 DESIGN CONSIDERATIONS FOR BRANCHING COLUMN SUPPORTED, FOLDED PLATE SHELLS

4.1 *A related system of interaction*

The relation between a folded plate geometry and branching patterns of column supports has been regarded in a previous study (Falk & von Buelow, 2008). The system was composed of timber-based plate units of pyramidal shape with zigzagging unit interfaces assembled into a space truss, supported by branching column supports in steel. Initially, different folding patterns, i.e. methods to define the facets of the roof, were explored and analogue thread models provided a branching pattern for the column design, which was further developed by using EC. A selected branching geometry was then utilized for an analysis in STAAD-Pro. In the study a structure comprising a plane assembly of plate units and four branching columns in a square pattern was regarded, thus a structure composed of four symmetrical tree structures with two free and two fixed edges. Both internal and external conditions were modeled. In the structure with four trees the column geometry changed in response to free edge conditions and leaning of the columns reduced the deflection around its perimeter. One of the aims of the continuation of the study was to elaborate the preconditions for interaction between shell and supports by varying the structural depth of the plate-assembly. The basic pattern of the plate geometry, generated through repetition of a single rhombic element, was fixed. The shape of the basic element is in this case the seed form of the pyramidal unit as well as of the overall shape. By varying interface angles of the basic unit the shape of the plane roof may be transformed into a curved assembly. The study focused on variation of form through variation of angles of the basic rhombus defining the geometrical properties of the three-dimensional basic unit. As reference the pattern of the basic units could be projected on a surface and then another set of models would develop, which would be related to tessellation or mapping of a mesh.

4.2 *Lattice-plate duality*

The relationship between lattice grids and plate based polygons, their interrelating duality and their related structural modes of action (Wester, 2002) provides a potential variation of form and utility noticeable in structural modeling, combination of structural modes of action as well as in constructed architectural results. The geometric properties studied in the folded plate roof above relies on three-dimensionality and pure plate-action but could be translated into or combined with bar-units resulting in an open or partly open space frame. The interface properties differ in the two cases but may very well be mutually adapted and combined for optimized utilization of e.g. a roof with open and closed sections. Stabilization of edges and control of the shape may in that case need an additional bar system.

The intimate relationship between bar and plate systems has been utilized in a study of plates in structural tensegrity applications (Falk, A. & Tibert, G. 2005). In that case the basic plate tensegrity module, i.e. a cable-stayed plate, was analyzed by converting the plate into an equivalent framework of bars, in which a square plate was represented by a quadrangular bar and node system triangulated through cross-bracing.

5 AN EXAMPLE OF THE PARAGEN METHOD APPLIED TO A LARGE STRUCTURE

5.1 *The complex roof system and form*

The project presented as an example consists of a roof covering an approximately 50x50 square meters area, located in Milan, Italy. It is being developed by following a performance based design approach that aims at shaping the roof system on the basis of performative analyses; these are used to inform the design in its early phase through performance-based simulations. Specifically, the geometrical properties of the roof are being investigated with respect to its structural performances and the control of the solar energy that passes through and reaches the interior spaces. The project is being used as a case study for further development of the ParaGen method. The design process aims at an integral approach for a combined exploration of the selected performances.

More specifically concerning the requirements for the solar energy control, the roof is expected to mediate on one hand the thermal and daylight comforts that are required in the spaces covered by the roof, and on the other hand the local climate, which would easily lead to the risk of summer overheating. In order to limit the solar heat gain by allowing indirect light, the roof is being designed as a system of south-oriented opaque panels and north-oriented transparent panels. The overall shape is being explored in different curvatures by creating top points where heat extraction can occur based on stack effect. The structural system of the roof is being explored in two options, either as a grid shell underlying the cladding panels or as a system of folded plate structural panels. In this paper the first option is being analyzed.

In the context of the first option, the overall roof is modeled as a NURBS surface and tessellated with a hexagonal pattern structural grid. The grid is then populated with three-dimensional components representing the cladding modules, while a set of four branching columns supports the structural grid above the ground. Two parametric models have been made so far; the first one focuses on the roof and is structured in a hierarchical chain of dependencies that includes variables regulating the curvature of the roof, the density of the tessellation and the inclination of the cladding panels; while the second one explores the curvature of the roof in relation to different proportions in length among the three branches of each column.

During this first phase of the work, the problem has been in fact subdivided in separated subdomains which are preliminarily explored. This was due to the complexity of the system in combination with the development of the ParaGen method. Specifically, the choice of separately analyzing on one hand the grid with respect to its structural performances and on the other hand the cladding system with respect to its solar energy transmission has been made both to separately test for the system and to allow a preliminary understanding of the different factors affecting the design.

In this context, this paper specifically tackles the work preliminary done on the structural performances of the grid shell and its supports; and next section explains the parameterization process of the structural grid and its supports.

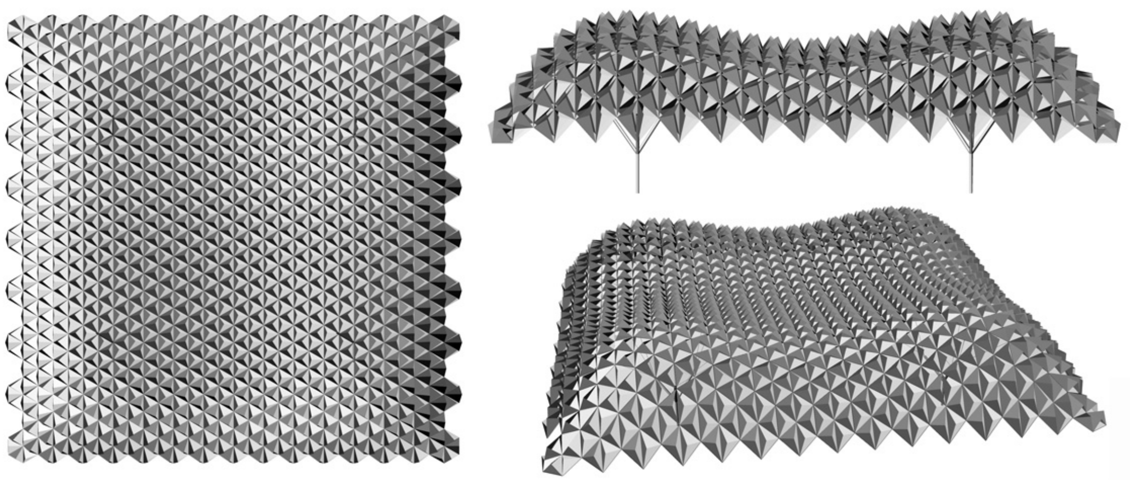

Figure 5. Roof system.

5.2 *The base parameters of model*

The structural grid has been modeled based on a NURBS surface of UV order six, and generated on a matrix of six per six control points. Eight of them have variable height (z Cartesian coordinate), four independently and four as a group moving together in the middle area of the surface. This allows shaping the surface with four lateral and one central variable peaks and/or on a dome-like configuration. The surface has been tessellated with the hexagonal pattern, for a fixed total of 247 hexagons. Hexagons are regular on the projected ground plane.

The supporting columns have been modeled based on straight lines. Each of the four branching columns is divided into three parts with variable lengths and supporting nine vertexes of the hexagons with a base point located on the XY ground plane. Each base point is in correspondence to the center of the four quadrants of the square surface. From the base points, the bottom segment of the supports start by pointing toward the centroid of the nine top points; while each of the middle parts points to the centroid of its respective group of three top points. This effectively orients the branches so as to minimize bending moments.

The parametric model defined in this way can generate approximately 21600 different instances of the geometry as a combination of various curvatures of the roof and various configurations of its supports. The generation of the instances is regulated by seven variables, the five z coordinates and two absolute values setting the proportions of the branching columns.

5.3 *Structural design parameters*

Although the folded plates were included in the parametric GC model, they were left out of the structural analysis because they play primarily a roll of cladding in this case. At this stage of design in order to have a gage of relative structural efficiency, the weight of the entire system was calculated. A single uniform load of approximately 1.5 kN/m^2 was used to simulate the load of cladding and moderate snow or roof live loads. The dead load of the steel structure was added in as a separate load. Standard steel pipe sections were used for member sections. The structure was analyzed using STAAD.Pro and all members were sized by the US steel code (AISC – ASD). The design process was iterated several times to get convergence of member sizes.

5.4 *Results of trial*

Figure 6 shows a sampling of the forms generate by the ParaGen method. The lighter forms were actually the ones which reduced the size of the humps thereby reducing the amount of material in terms of linear meters

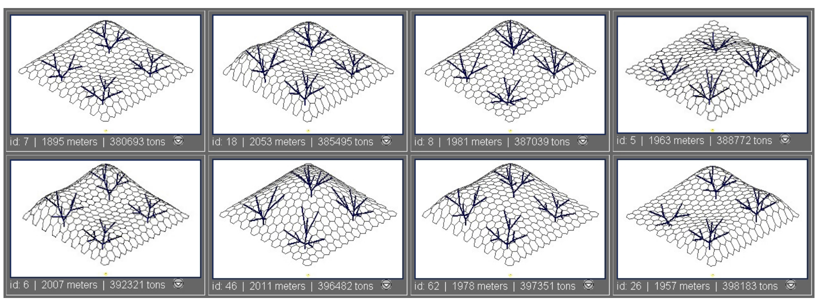

Figure 6. A selection of solutions arranged by increasing weigh.

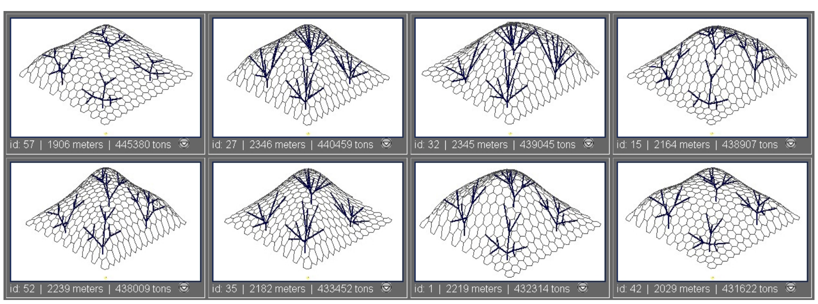

Figure 7 A selection of solutions arranged by decreasing weigh.

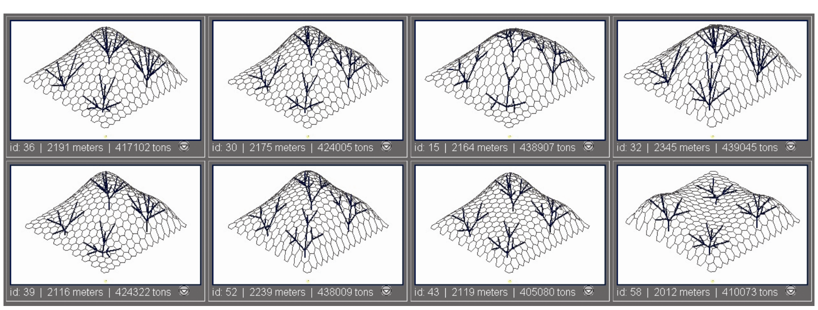

Figure 8 A selection of solutions based on a variable causing a lump on the upper side.

6 CONCLUSIONS

6.1 *Conclusions*

The performance based processes described in this paper aim at exploring the geometrical properties of a design approach utilizing performance evaluations in an early conceptual phase. The use of the ParaGen tool is shown to support the designer in exploring wide ranges of design alternatives as well as in defining, selecting and managing varying degrees of structural and architectural complexity. The genetic algorithms are used as a search method to guide the generation of different instances of the design towards an optimized range of solutions. The combination of parametric design with genetic search is proposed as a possible support to manage the generation of alternative design configurations through a limited set of variables. The examples discussed in this paper show the potentials of the ParaGen method. The method along with results are analyzed, and critical aspects are pointed out which require further development of the tool or specific attention in being approached by the designer.

Focusing on the latter, the fundamental role played by the selection of the design criteria is recalled. This has to do with the understanding of the design requirements on one hand and with their representation in the model on the other. The prerequisites offered by the tool supporting an explicitly iterative approach between designer and tool are appreciated. Selection of suitable criteria is mainly based on the preliminary identification of the range of performances that are related with the satisfaction of the various design expectations, which in the case of contemporary architectural and structural design may be manifold. Structuring the geometrical model to generate different configurations that are meaningful for these selected performances is mainly based on the understanding of the relations between the geometry and the analyzed performances. This is the most crucial key to allow a suitable parameterization of the model; and the success of the ParaGen design exploration is mainly based on this key aspect.

The tool is meant to support the designer in the investigation of alternative solutions. But it should be noted that the emphasis is on "support", and is not intended as a substitute for the designer's the understanding of the explored design aspects. As a practical consequence, a very close interdisciplinary collaboration is needed in the initial phase of the process, even before starting any modeling. This is presented here as a positive aspect, which increases the information input to the conceptual design phase, as compared to the traditional parallel and consequential phases of design followed by analyses. A second great advantage offered by the tool consists in the active role of the designer during the optimization process. ParaGen allows in fact the designer or designing team to direct the evolution of the geometry in a certain desired direction, using the performances as secondary input.

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