Performance-oriented design of large passive solar roofs

A method for the integration of parametric modelling and genetic algorithms

Michela Turrin[1], Peter von Buelow[2], Rudi Stouffs[3] and Axel Kilian[4]

[1,3]Delft University of Technology, The Netherlands, [2]Michigan University, Michigan, [4]Princeton University, New Jersey.

[1]http://wiki.bk.tudelft.nl/designInformatics/Michela_Turrin, [2]http://www-personal.umich.edu/~pvbuelow/, [3]http://www.tudelft.nl/rmfstouffs, [4]www.designexplorer.net/

[1]M.Turrin@tudelft.nl, [2]pvbuelow@umich.edu, [3]R.M.F.Stouffs@tudelft.nl, [4]akilian@princeton.edu

Abstract. The paper addresses the design of large roof structures for semi outdoor spaces through an investigation of a type of performance-oriented design, which aims at integrating performance evaluations in the early stages of the design process. Particularly, aiming at improving daylight and thermal comfort under large structures, the paper focuses on the exploration of passive solar strategies to reduce the need for imported energies. Referring to this context, the potential of parametric modeling is investigated with respect to performance-oriented design and a method, denoted ParaGen, is presented, based on the integration of parametric modeling and genetic algorithms. The potentials of the method are shown by discussing a case study, the roof SolSt. The design process of SolSt is based on parametric variations of its curvature, the density of its modules and the geometry of its cladding and explored based on the daylight and solar exposure of the covered spaces.

Keywords. Performance-oriented design; parametric modeling; genetic algorithms; passive solar strategies; large roofs.

Introduction

Historical cities bear testimony to the traditional importance of semi outdoor spaces in urban areas. The Vittorio Emanuele public covered gallery in Milan is just one of many examples of Mediterranean shaded squares, streets, courtyards, and historic commercial galleries. Contemporary cities increasingly integrate such structures in the urban fabric. This is due to the increased demand for representative structures that mark the built environment, such as in the case of representative halls and atria, and for space utilization independent of the weather conditions, such as in the case of stations and shopping centers. Therefore it has become more common for architects and engineers to engage in the design of large roof structures for semi outdoor spaces. In this paper we focus on performance-oriented design, integrating performance evaluations in the early stages of the design process. For large roof designs, aesthetics, structural performance and economics tend to dominate the design process. However, the current increased emphasis on energy-related aspects generates new challenges. Particularly, the use of renewable energy resources, including both active and passive systems, needs to be confronted in the design. These systems play a key role in controlling the microclimate beneath large roof structures. A great example of such integration between active and passive strategies is offered by the roof designed for the Masdar Headquarters by Adrian Smith, Gordon Gill and Robert Forest with their team [FIGURE 1].

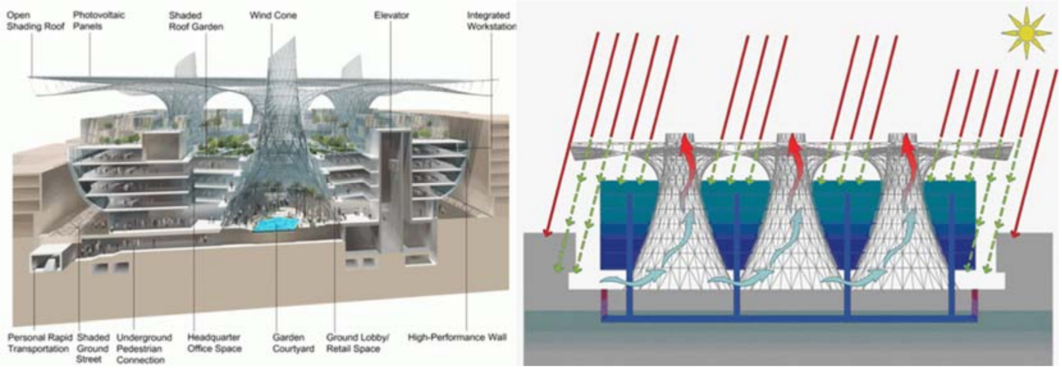

Figure 1
Diagrams of the roof of Masdar Headquarters[images courtesy of Adrian Smith+ Gordon Gill Architecture].

By aiming at improving daylight and thermal comfort under large structures, the authors focus the paper on the exploration of passive strategies to reduce the need for imported energy. Specifically, we address the aspects directly affected by the geometry of the design. Due to the large effects of the geometry on the performances of long span roofs, including performance simulations early in the evaluation of geometrical alternatives becomes crucial. We discuss parametric modeling as a possible support for an interdisciplinary design process; further, a genetic algorithm based tool, ParaGen, is discussed to loop the parametric generation of design alternatives with performances evaluations.

Passive solar design for large roof structures

In European, moderate climates, passive strategies for thermal comfort are based on capturing maximum solar radiation during the winter days, on the internal preservation of the accumulated heat during the winter nights, and on avoiding over-heating during the summer days. This approach is frequently integrated with natural ventilation at night to cool the thermal mass of the building. When focusing on large roofs, strategies for passively improving the thermal comfort involve a large set of combined systems for heat gain reduction and passive cooling. Passive heating as well as passive cooling rely on controlling airflow, controlling direct solar radiation and the mean radial temperature of the roof, and using thermal mass; furthermore, evaporative (adiabatic) cooling for reducing the maximum temperatures is to be taken into consideration when focusing on passive cooling. Examples are numerous, including the microclimate created underneath the well-known large domes of the Eden project in Cornwall, as well as the recent Dolce Vita Shopping Centre in Lisbon and, among atria where specific attention to climate issues was needed, the atrium spaces in the Wynn resorts in Las Vegas.

We present some example data on this topic based on a case study, the Vela roof in Bologna (Italy). This case study was developed as a collaboration between the architects and engineers responsible for the overall building project which includes the roof, and an interdisciplinary team at Delft University of Technology. More detailed descriptions can be found in previous publications (van Timmeren and Turrin, 2009; Turrin, 2010). The case study focused on passive strategies for reducing the summer overheating of the spaces underneath the roof. This case study can be summarized in investigations for increasing the airflow underneath the Vela, reducing the direct solar exposure of the covered spaces, reducing long wave radiation from the roof, and reducing the maximum temperatures using adiabatic cooling. Among the large set of data related to each of these aspects, a few key examples are recalled, referring to the three levels of the covered spaces: (a) the ground floor with a semi-outdoor public square, (b) the first floor with a terrace covered by the roof and (c) the second floor with walkable roofs for public use. By analyzing a reference geometry, a daily maximum Physical Equivalent Temperature (PET) of 35.1 Celsius degrees for (a), 37.3° for (b) and 39.7° for (c) were expected under the roof in July for a cladding with 50% transparency. Decreasing the transparency by about 25% using clear opaque colors solar exposure was reduced without increasing the long wave radiation, and allowed a significant increase in comfort, reducing both the time and area with maximum daily PETs between 38-42 degrees (c). However a 70% opaque cladding affects the daylight, which was shown to be not sufficient. Introducing a cladding system based on a three-dimensional geometry with a north-south oriented shading printed pattern [FIGURE 2] was evaluated to be of great help in limiting the direct solar exposure underneath the roof while allowing the transmission of indirect daylight. This allowed avoiding maximum PETs over 34-38 degrees also in the most critical level (c). Fountains, ponds, sprayed water mist for adiabatic cooling and slightly increased air flow were combined as well, allowing maximum PETs between 30-34 degrees, which were considered acceptable when compared to the outside.

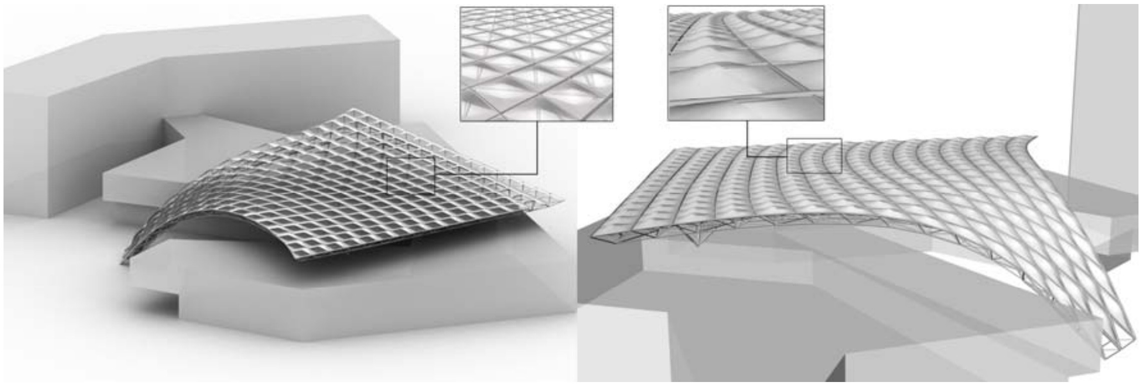

Figure 2
The designed ETFE cladding viewed from the North and from the South directions.

The geometry of the roof at its different scales plays a key role in this heating and cooling strategy as reflected in the provided data. Specifically, over a total PET reduction of about 25%, about 12% was due to the combination of geometrical and material properties of the cladding. In addition to the discussed geometry of the cladding, evaluations at a larger scale can be added as a key factor in driving the airflow. Furthermore, geometry becomes a key factor in bridging different performances, such as, in the case of large roofs, structural morphology and cladding systems.

Parametric modeling and genetic algorithms as design support

Referring to the context of performance-oriented geometry for passive solar roofs, the potential of parametric modeling is investigated as design support during the early design phase. Parametric modeling allows both geometrical entities and their relationships to be represented. 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. The instances of the parametric model can be explored with respect to a given set of design criteria, based on the specific performances used as key drivers for the design.

In order to achieve a solution space for the parametric model that is meaningful with respect to the selected performances, the parameterization process has to be based on the interdisciplinary knowledge shared among the various experts involved in the process. This requires preliminary brainstorming based on systematic interdisciplinary collaborations. In this way, the process can benefit from the automatic generation of a large set of meaningful geometrical alternatives; and the knowledge that such a process forces collaboration in the preliminary phases of the design is an added value of the parametric model. However, due to the breadth of the solution space, its exhaustive exploration is not possible when left to the intuition of the designer. The identification of the better solutions remains problematic. 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 performance, is proposed here to solve this problem. Directly looping the parametric generation of design alternatives with performance evaluation tools and orienting such generation toward the desired performance is the key principle of the proposed solution. Specifically, a method, called ParaGen, based on the integration of parametric modeling and genetic algorithms, is presented.

The ParaGen tool

ParaGen is a parametric design tool using genetic algorithms for the exploration of form based on performance criteria. Its implementation is under development at the University of Michigan, Taubman College, where it has been used for structural form optimization. Based on current collaborations with Delft University of Technology it is being extended toward the interdisciplinary optimization discussed in the previous sections of the paper.

The version of the tool discussed in this paper makes use of a parallel network of PC's using Windows XP and a web server, to run a series of both custom written and commercial software packages. These are looped in a cycle based on three main components:

(1) The selection of variables: a genetic algorithm (GA) provides the values of the independent parameters using techniques of selection, recombination and mutation.

(2) The generation of forms: a parametric modeler generates the geometry using the variables provided by the GA. Currently this step is based on Generative Components (Bentley Systems), but the system is open to different parametric modeling software (such as Grasshopper or Digital Project).

(3) The analysis of the generated forms: the geometry provided by the parametric modeling software is evaluated in terms of performance. Originally, this step used STAAD-Pro as FEA software for structural evaluations. It is being now extended to the use Ecotect as simulation software for thermal and daylight performance.

The cycle

Once a parametric model is established based on a range of independent parameters having a dependency chain that is meaningful for the performance to be analyzed, the first ParaGen cycle can be run. For this first cycle, the GA system generates an initial set of random values for each of the variables. This set needs to be relatively wide ranging in order to include a large variability of the design alternatives. These initial combinations of variable values are downloaded from the server to local PCs as Excel files for processing by the parametric modeler. This requires importing the variable values and using them to produce the startup population of geometrical solutions. As each geometrical instance of the parametric model is established, the solution is then processed through the rest of the ParaGen cycle. In this specific case they can be processed through STAAD-Pro or Ecotect or both, according to the desired performance information. This determines the structural or thermal or daylight characteristics associated with the solution. At the conclusion of the local part of the cycle, the original set of variable values, the performance results, along with data files useful in a more detailed assessment of a particular solution are uploaded to the web server. In this way, jpg, dxf, or wrl files are made available for visualizing the geometry of the solutions. Also STAAD and/or Ecotect data files are saved for a more detailed inspection by the designer of the performance characteristics. Both the variable values and performance results are maintained in a SQL database, and linked to the data files so that the designer can retrieve them all through the web interface. After the initial random population is established, new parents are selected based on the better performing solutions. The selected parents are passed to the GA program where they are bred to yield a new child data set based on half uniform crossover of the variable values. The children data are 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. This leads to the identification of good performing solutions toward which the generated populations converge.

The interaction with the designer

One aspect needs to be discussed with respect to the convergence of the population toward good performing solutions. The ParaGen method aims in fact at exposing a range of ‘pretty good’ solutions that can be compared with one another. In this, ParaGen is different in focus from traditional optimization methods. While in traditional optimization, a single best solution is sought for a given set of objectives applied to a specific problem, ParaGen is geared more toward allowing an exploration of a range of solutions rather than limiting the focus to one single ‘best’ solution. With respect to this, the ParaGen tool aims at combining both programmed objectives (such as least weight of structural members or solar energy transmittance) along with subjective selections made by the designer. In this way, the program can take into account for example the visual appearance of the solutions, based on designer preference. The visually oriented approach of the ParaGen method offers advantages that can aid the designer in finding an appropriate solution by making preferential selections in ill-defined problems that are not numerically expressed by the performance criteria. The tool aims at allowing the comparison of solutions side by side, which quickly highlights the differences in form that 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. Based on this aim, the GA program in ParaGen allows new solutions to be generated either by breeding two parents, or by mutating one parent based on the preferences of the designer. Operatively, all of the generated design alternatives are visualized via a web interface. The integrated sorting feature makes it possible for the designer to analyze the population in different directions. The solutions can be sorted twice successively based on any variables defined in the parametric model or the performance results thereof. Besides allowing the designer to view and sort through the generated solutions, the system provides access to select the eventually desired parents. The interactive selection feature of the website integrates the automatic breeding in a continuous cycle based both on pre-defined objectives and on the intervention of the designer to address the generation of solutions based on other preferences.

The example of SolSt, a large roof in Milan

The potential of ParaGen in exploring high numbers of variations of complex geometries for the design of passive solar roofs is illustrated through another case study, currently under development. The project consists of a free-form roof covering an area approximately 50m x 50m, and located in Milan, Italy, called SolSt. Similarly to what was discussed for the Vela roof, this test case is expected to contribute to the required thermal and daylight comfort in the covered spaces, and to temper the local climate to avoid the risk of summer overheating. Figure 3 shows the overall concept of the roof.

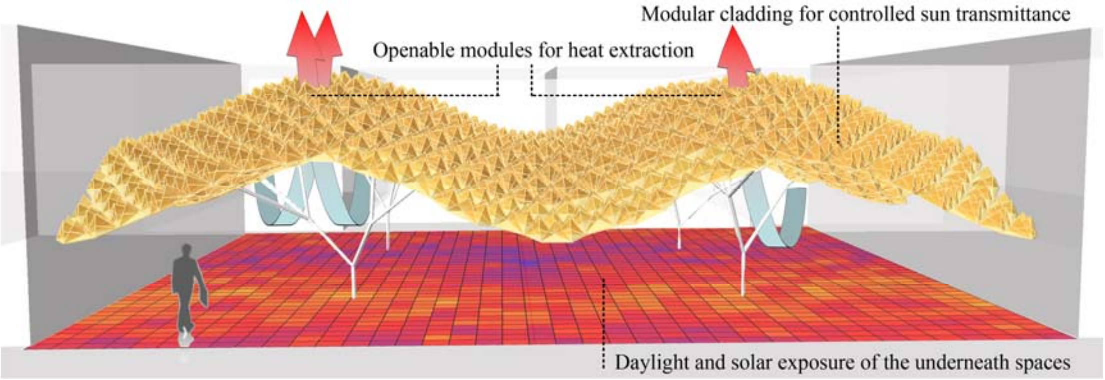

Figure 3
Scheme of the concept for SolSt.

In order to facilitate the air flow for cooling, the overall shape is designed based on roof peaks where heat extraction can occur through top openings due to the stack effect. Further, in order to limit the solar heat gain while allowing indirect light, the roof is designed as a modular system of cladding panels, whose material properties and geometrical configurations are explored based on performance evaluations. This paper focuses on limiting the potential for summer overheating. However the roof is meant to work as a system including also winter performances and requirements. From among various requirements, the need to regulate the airflow by closing the top openings is considered here.

Overall shape and tessellation of the roof

The overall roof shape has been explored based on two parametric descriptions of its geometry. The first exploration made use of a NURBS surface modeled through a set of control points whose Cartesian coordinates act as independent parameters. In order to tessellate the surface by defining the main structural and the cladding's geometry, the surface has been populated with a set of points based on UV coordinates. Independent parameters controlled the density and the distribution of the points. These points serve as nodes to variously tessellate the surface based on different polygons. In this case, the overall shape was based on a first level of parameterization while the positions of the nodes were based on a second level of parameterization and were dependent on the NURBS surface. This method was successfully taken from previous approaches, such as the one used for the Vela (Turrin, 2009). However the need to integrate reconfigurable modules to open and close the top openings led to a variation in the approach.

In order to facilitate the design and the integration of the openable parts, the peak surfaces are constrained geometrically. More specifically, a horizontal plane intersecting the top part of the peaks was expected to generate an approximately circular section. In order to achieve this condition, the overall shape has been described by positioning a set of points based on mathematical functions. These points can also serve directly as nodes for the tessellation. Figure 4 illustrates the parameterization of the model.

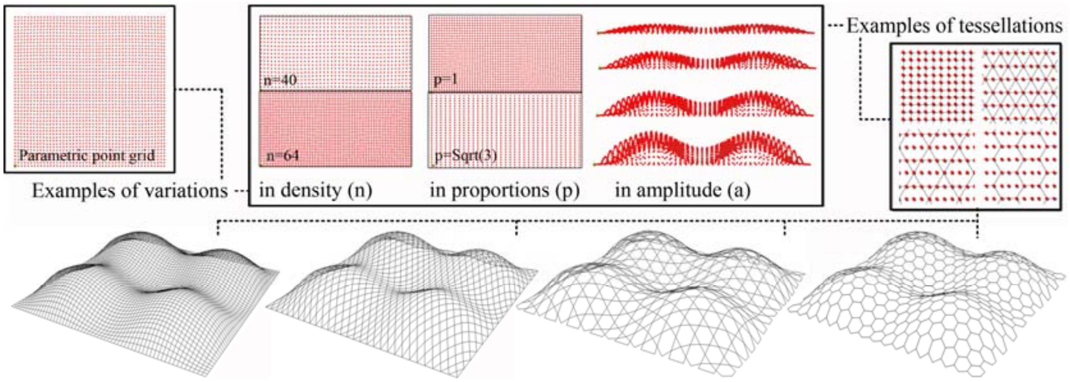

Figure 4
Examples of parametric variations of the point grid and examples of tessellations.

Particularly, the positions of the points are described based on Cartesian coordinates. The x and y values define the density of the grid, based on an independent parameter *n*, as well as its overall dimensions; the z value is described based on a sin function whose amplitude is an independent parameter *a* regulating the height of the peaks. The sin function is doubled by following both the x and y directions in order to achieve the desired curvatures in both. Further, the edges of the roof are expected to be on a planar square; in order to meet this condition, the z values are smoothly driven towards 0 when close to the edges by multiplying the sin function with an additional function. The distribution of points so obtained is used to tessellate the roof based on quadrangular, triangular, hexagonal polygons or combinations thereof. The density of the point grid can be regulated in the two directions according to the needed proportions, through a third independent parameter *p*.

Performance oriented cladding system

The cladding of the roof is designed as a modular system, propagated over the overall shape based on the tessellations obtained as described above. Various cladding options are explored based not only on the different tessellations, but also on different topologies of modules for each single tessellation as well on different geometrical variations of each single topology.

This section presents an option based on hexagonal modules and combining south-oriented opaque panels and north-oriented transparent panels. Independent parameters locally regulate the inclination of the panels. The roof is evaluated based on the daylight factor and the incident solar radiation of the spaces underneath, in the hypothesis of transparent glazed panels and glazed panels with 90% light color serigraphy. [FIGURE 5].

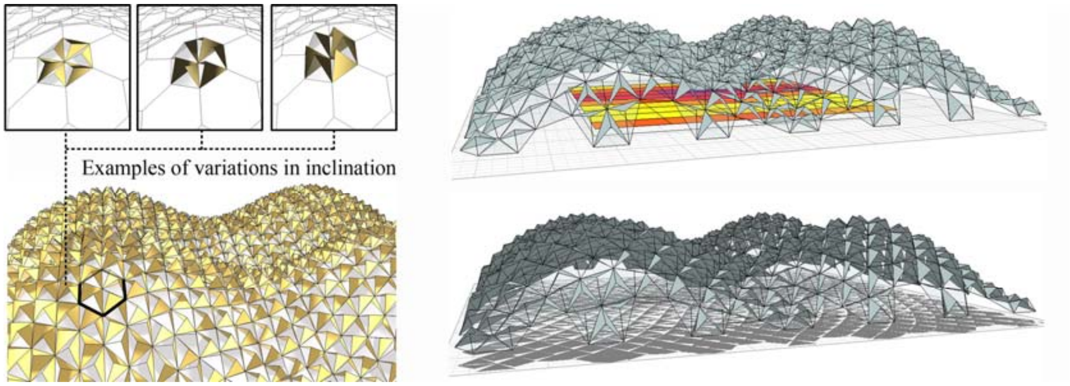

Figure 5
Examples of parametric variations of the cladding and performances evaluation of one instance of the roof, concerning the daylight factor and the incident solar radiation in the covered spaces.

ParaGen is used to explore the parametric design alternatives looking for the maximum daylight factor and the minimum incident solar radiation. [FIGURE 6].

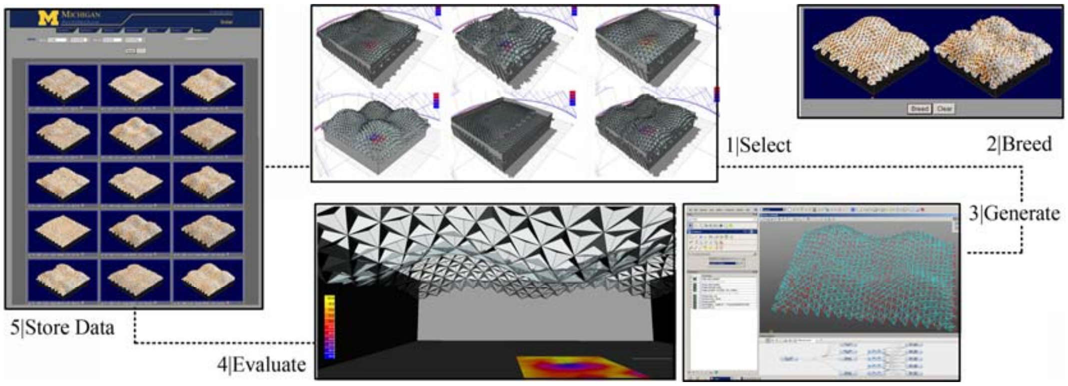

Figure 6
The ParaGen loop.

The first population has shown the emergency of two main strategies. On one side high curvatures of the roof lead to differentiate the North oriented and the South oriented areas based on the configuration of the shading elements, which have increased dimensions and inclination when facing the South. On the other side, similar performances are achieved by a family of solutions in which the flat configuration of the roof leads to homogenously distributed highly inclined cladding panels.

Tessellations for integrating reconfigurable modules

For the option presented above, a separate tool was developed for exploring the tessellation when constraining four hexagons on the top of the peaks. Centering the polygons on the peaks allows in fact to obtain four regular and flat top polygons. This issue was initially approached in GC, by sliding the tessellation according to pre-calculated values in order to stretch and squeeze the polygons in the lower parts of the roof. However, the method has shown some relevant limitations, such as the effort to predefine the deformed tessellations. As an alternative, an application was developed in Processing, based on the use of particle springs. While guaranteeing the top hexagons being regular and flat, the application simulates the hexagon distribution with a particle spring system with the particle nodes sliding on the mathematical surface function [FIGURE 7].

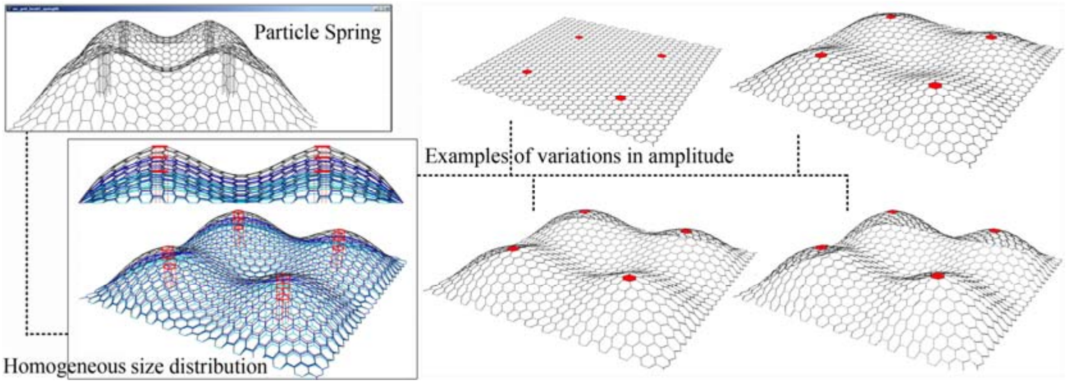

Figure 7
Examples of particle spring based tessellation for various heights of the peaks

Conclusions and further work

We presented parametric modeling and the coupled GA method ParaGen as a support for the early phase of the design of performance oriented large roof structures. A successful example of the potentials offered by this combination was shown based on a current case study. The guidance given by the search method as a way to explore the solution space of the parametric model presents a first clear advantage. Secondly, the possibility to freely explore the generated solutions by sorting them according to different criteria provided assistance in understanding the relations between geometric variations and performances. Thirdly, generalizing the parametric model by integrating different possible tessellations offers great potential to easily enlarge the solution space being explored. Concerning this aspect, an example is offered by the analyzed cladding system, which shows a limitation due to an almost proportional variation between the incident solar radiation and the daylight factor of the spaces underneath. The set of possible tessellations already embedded in the parametric model allows for the easy exploration of different cladding modules, which are currently being investigated to decrease the proportionality of the variations between incident solar radiation and the daylight factor. At the same time, the current explorations are being integrated with the winter scenario; and while the optimization regarding the summer conditions converged toward solutions with minimum incident solar radiation and maximum daylight factor, in winter both are maximized. Comparing the geometries optimized for the two different seasons is expected to help in estimating also the eventual benefits provided by adaptable design solutions (such as adjustable cladding).

Acknowledgements

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