Computational Morphogenesis in architecture: structure and light as a multi-objective design/optimization problem

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ABSTRACT: This paper deals with a multi-objective design/optimization grid-shell problem. Structural behavior and light absorption/shading have been selected as fitness functions. Such performance criteria can separately lead to different and divergent optimal solutions but, if they are considered as a whole, they are expected to result in several equivalent or similar sub-optimal shapes. This multi-objective optimization problem has been performed here with the aid of a Genetic Algorithm (GA). GAs explore and search widely for suitable solutions and, in this way, they become design tools rather than solution ones. Three benchmarks were established and then a more complex application was made to an existing case study, i.e. the Esplanade in Singapore, designed by DP Architects (DPA) and Michael Wilford & Partners (MWP).

1 INTRODUCTION

Natural Light is a key aspect in architecture since ancient times and has been for centuries until contemporaneity. In 1923, Le Corbusier wrote that “Architecture is the masterly, correct, and magnificent play of masses brought together in light”, a difficult statement to ignore but which that immediately raises a fundamental question – how is it possible to design using light as a performance parameter?

In several cases, darkness is also acceptable, as Tanizaki described in his book: “In praise of shadows” - direction, intensity and refraction of light can define bright, as well as shaded environments, stimulating different emotions and perceptions of space.

Moreover, light carries energy, thus its management has implications on the thermal physiology of buildings and organisms. The intricate interplay of light with structural aspects may be better understood if we consider one of the peak moments in history when structure, spatial differentiation, surface, ornament and light choreography coalesced in an extraordinary production of great examples, such as King’s College Chapel. Because of its intrinsic nature, perceptual reverberation, as well as the emotional effect that certain light conditions or certain structures inspire are subjective, contingent implications, for which it is difficult to find a mathematical formulation.

However, the measurable effects of their performance can be incorporated as design parameters that could initially be considered to investigate the relationship between light and structure in architectural design as an optimization problem. For instance, in the case of grid-shell roofs for libraries and museums, the quantitative aspects of natural light can be optimized, i.e. setting the openings to control the direct and indirect contributions, but also to verify that the illuminance value for reading tasks is above a certain threshold. Furthermore, considering the production of electric energy by photovoltaic panels, the light absorption on receiving surfaces can again be considered as a well-defined performance. In some other cases, direct light is not controlled and design efforts are focused on providing the building with kinematic structures that are able to respond to solar stimuli through movements. Inspired by the phototropism of some plants, this approach is mainly used for shading and energy production reasons.

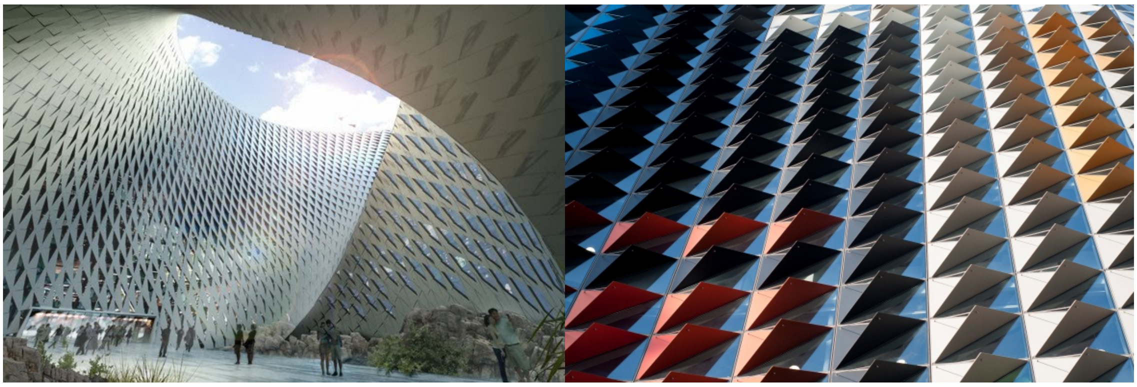

Figure 1. Left: Astana National Library by BIG. Right: RMIT by Lyons.

In projects such as the Astana National Library, designed by BIG (Figure 1, left), form, structure and light have been integrated in a complex hierarchy to generate the 'skin' of the building – a grid-shell, which has been shaped around a Moebius ring, accommodates shading devices in its structural mesh. The same has also been used to design the envelope pattern. Instead, at the RMIT Swanston Academic Building, designed by Lyons in Melbourne (Figure 1, right), the lack of interplay between structural form and light can be considered a missed design opportunity. The project is characterized by a colored envelope whose triangular elements and shading panels just compose an aesthetic pattern, but do not perform any structural function. Its construction required a heavy frame to support its weight, which also raised valid questions amongst architects and academics on the overall rationality of the building.

In this framework, this paper deals with a multi-objective design/optimization grid-shell problem. Grid-shells are a family of structures resistant in form, in which the evaluation of their mechanical behavior could be considered to be as important as the control of the sunlight absorption/shading on their glass surface. Structural form and light are used as performance parameters and, starting with a simple benchmark, the two fitness functions are first tested separately and then together. This shows how their single contributions can affect the search for an optimal shape in different and divergent ways. Inspired by the geometry of the RMIT building façade, the benchmark is set up with only two design variables in order to allow a graphical 3D representation of the candidate solution performances as a 'fitness landscape'. The multi-objective morphogenetic procedure is then applied to a more complex built case study – the Esplanade in Singapore, designed by DP Architects (DPA) and Michael Wilford & Partners (MWP). See Figure 2, on the left.

In architectural design, the definition of a parametric system with boundary conditions, design variables, solution domains and fitness functions, together with the understanding of how the optimization process actually searches for suitable shapes, is probably more important than reaching an optimal result. Mere problem-solving techniques become orientation devices for the computational exploration of the process of morphogenesis.

2 MULTI-OBJECTIVE OPTIMIZATION AS A DESIGN TOOL

In biological systems, shape determines function, and the energetics of function dictate the optimal structure required (Hyde et al., 1996). For instance, the morphology of a body organ is dictated by many factors, which depend on the complexity and energies involved in its function. Within this framework, branching optimization in blood vessels is still at work, but accepts the shape of the organ as an operational drawback because it has limited influence on its general morphology. The case of structural and light optimization is of particular interest, in terms of multi-objective and generally non-convergent performances. As shown in Figure 2, on the left, the same structural shape of a grid-shell can be subject to different natural light situations. According to the building orientation, the optimization might converge or diverge to diverse optimal solutions. Even in the same structure (Figure 2, on the right) the different orientations of the roof surface could drive the optimization towards unexpected sub-optimal solutions (which could satisfy the multi-objective fitness function, but be very distant from the optimum).

Figure 2. Left: The Esplanade designed by DPA. Right: Central European Time designed by Kas Oosterhuis.

2.1 *Implementation with Genetic Algorithms (GAs)*

This multi-objective optimization is based on an evolutionary population-based technique - Genetic Algorithms (GAs).

GAs are very time-consuming optimization algorithms and generate a large set of tentative solutions to a problem (populations of individuals), which are evaluated according to an objective function (fitness function) until a determined termination criterion is satisfied. GAs can be used to explore the complete solution domain of the problem, not only providing an optimal solution, but also making local minima and unpredictable sub-optimal solutions emerge. This could in general be of more interest from a design point of view.

3 BENCHMARK APPLICATIONS

3.1 *Digital environment*

A first implementation of multi-objective optimization has been developed on simple benchmarks with the aid of the commercial software listed below.

(1) a three-dimensional NURBS modeler (Rhinoceros), including its parametric plug-in (Grasshopper), which allow users to visually handle parametric geometries and data;
(2) a Finite Element Method (FEM) solver – Karamba – technically provided as a plug-in for Grasshopper and directly integrated into Rhinoceros;
(3) a tool for solar analysis – Ecotect, GeCo – which performs parametric solar analysis, starting from any mesh;
(4) an optimization algorithm – Galapagos – which is directly integrated in Grasshopper. It can easily be used as a black box, just by setting the basic parameters, such as population size, percentage of reproduction and mutation frequency.

Such tools have been chosen because of their user-friendly interface and have specifically been used without resorting to custom-made components. With this choice, architects are provided of a simple, rapid and efficient way of dealing with the computational morphogenesis of building during the conceptual phases. A simple tool was adopted especially for the FEM solver, since it is essential to set up a process in which the data remain explicit and easy to control.

3.2 *Parametric definition and solution domain*

The benchmark has been conceived as a simple surface *S'(x, y, z)*; the planar projection of *S'* is square-shaped with a 2x2m^2 area. The geometry is defined by two parameters: $h1 \in [0;2] \wedge h \in \Re$; $h1 \in [0;2] \wedge h \in \Re$. From these, 4 corners and 4 midpoints are determined: *A=(0, 0, h1), B=(0, 2, h2), C=(2, 2, h1), D=(2, 0, h2), H =(1, 1, (2-1/2h1-1/2h2)), H1=(0, 1, 1/2h1+1/2h2), H2=(2, 1, 1/2h1+1/2h2), H3=(1, 2, 1/2h1+1/2h2), H4=(1, 0, 1/2h1+1/2h2).*

It can be assumed that $S'(x, y, z) = S'(h1, h2)$; its spatial configuration can therefore be flat, with a positive double curvature, or with a negative double curvature (Figure 3).

Once the NURBS surface has been defined, a mesh discretization is applied to it. A FEM solver is used to perform the structural analyses. $S'(h1, h2)$ is divided by 6 x 6 *u, v* grid and a $S(h1,h2) \approx S'(h1,h2)$ diagram is obtained.

In order to further improve light incidence on the faces, half of them are set with a tilt angle $t=30°$. Spatial model $S(h1,h2)$ can be analyzed for specific behavior (i.e. structural, solar,…) by setting specific fitness functions $f_i(h1,h2)$. A third fitness value, that can be used to build a 3-dimensional landscape domain through discrete points $(h1,h2, f(h1,h2))$, is obtained for each $(h1,h2)$ couple. See Figure 3 - below.

3.3 *Structural fitness landscape*

A structural benchmark is developed by considering an $S(h1,h2)$ wireframe truss. An elastic spatial frame is considered made up of one-dimensional elements, loaded at the nodes and with the ground restrained at its four corners.

A unitary force $\boldsymbol{v}=(0,0,-1)$ is then applied at each junction, and a *dz* displacement is thus generated for each node. Where each *dz* tends to zero, $S(h1,h2)$ tends to optimum; this behavior reflects the architecture of the GA for which the fitness function has been imposed to minimize to $f_{st}(h1,h2)=\sum dz \rightarrow 0$. Evaluating the displacement summation allows both the local and global weaknesses to be considered, since each node has to contribute equally to the goodness of the solution. The solution landscape is normalized to $[0; 1]$ to show the absolute results. $f_{st}(h1,h2) \in [0; 1]$. The optimum is reached with a hypar for $(h1,h2)=(2.0,0.1)$; see Figure 3.

3.4 *Light fitness landscape*

The solar benchmark has been developed for the same model that was considered for the structure. In this case, shading panels have been added to the $S(h1,h2)$ wireframe truss.

The geometry is oriented by setting the *y*-direction northwards and the analysis location near Rome (41°53’35”N, 12°28’58”E). An evaluation period from 21st December 2012 to 21st June is then defined. The solar incident radiation *R* parameter has been evaluated over the mesh faces.

In order to find the optimum, a fitness function has been set within the GA to minimize: $f_{lt}(h1,h2)=(\sum R)^{-1}$. The higher the amount of absorbed solar radiation, the better. Like structural fitness, $f_{lt}(h1,h2)$ also depends on 2 parameters; a 3-dimensional solution landscape is therefore obtained. A global minimum is set for the light analysis for the obvious solution $(h1, h2)=(1.0,1.0)$; the surface is flat and the panels have a 30° tilt. See Figure 3.

3.5 *Multi-objective fitness landscape*

The multi-objective benchmark again tests the same model but, this time, a different fitness function is applied. In order to evaluate both performances, an aggregated function has been adopted to perform an a priori articulation of the preferences.

It was decided to consider a normalized structural fitness and a solar one, balance with two weight coefficients, *a* and *b*, and then finally to sum them. Dealing with absolute values allows two physical quantities to be blended into one: $f(h1, h2)=(a \cdot f_{st}(h1, h2)+b \cdot f_{lt}(h1, h2))$. $f(h1, h2) \in [0; 1]$.

Once a solution landscape has been defined, the optimization can be run through the GA. Since it was decided that the light and structure should be well balanced, $a = b = 0.5$.

A comparison of the solution landscapes reveals different behavior for the different candidate solutions. The structural behavior is polar-symmetric, while the solar behavior is not, since it depends on both the shape and solar exposure. The minima of the multi-objective are located in an area that mediates the structural and the solar domains; as can be seen in Figure 3, there are 4 local non-symmetric minima. The multi-objective optimum is reached for $(h1, h2)=(1.4,0.6)$.

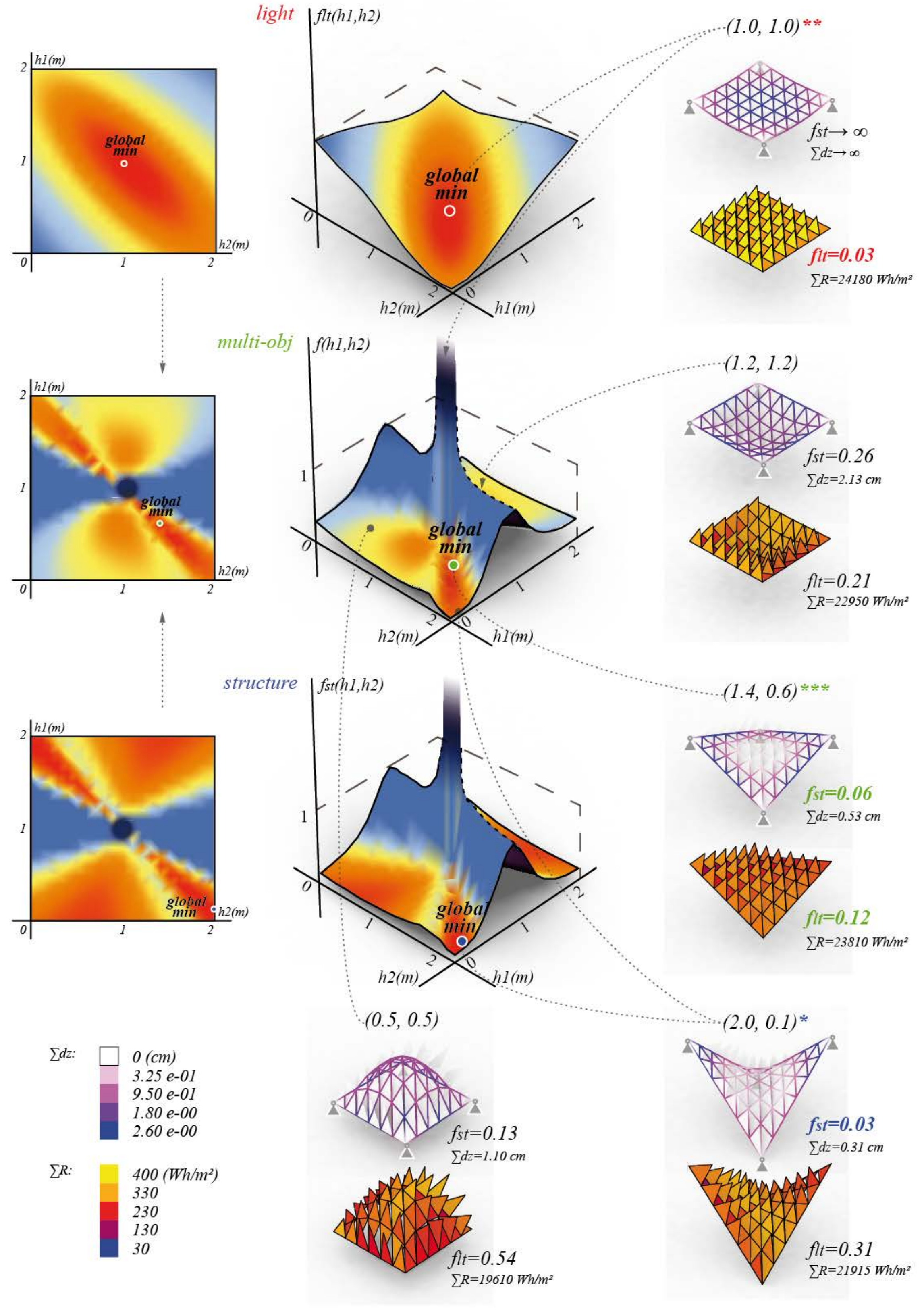

Figure 3. Left & centre: Landscape solution domains in 3-dimensions and in plan view. Right & bottom: Geometry population described for the structural (f_{st}) and solar (f_{lt}) fitness. The spatial configurations are identified within each domain, if significant. Structural optimum* has been reached for *(h1, h2) = (2.0,0.1)*. Solar optimum** for *(h1, h2) = (1.0,1.0)*. Multi-objective optimum*** for *(h1, h2) = (1.4,0.6)*.

4 CASE STUDY

Figure 4. The Esplanade, designed by DPA. Left: general layout. Right: details of the roof cover.

Finally, the multi-objective optimization described above has been applied to a real case study - the building complex called "Esplanade" in Singapore. This construction is characterized by two identical 'helmets', placed in orthogonal directions, as shown in Figure 4.

The truss-like base structure supports a grid-shell with triangular glass panels, which have been finished with 'scale-shaped' shading elements that design the surface skin. In this case, the structural behavior is as important as the control of natural sunlight, thus making the "Esplanade" a perfect project for the present application.

In order to simplify the process, just the grid-shell surface has been considered. This geometry has been modeled as a mesh surface, defined by 15 *n-th* control points. *G* is the ground projection of the geometry hub; $\boldsymbol{h_n}$ is the normalized vector applied from *G* to *n-th*. The coordinates of each *n-th* point are spatially defined by the product $s_n \cdot \boldsymbol{h_n}$. $s_n \epsilon [0,20]; n \epsilon [1,15]$.

The spatial coordinates of the boundary control points are fixed. Further details can be found in Figure 5. The NURBS surface has then been discretized according to the geometry of the real building and the shading elements have been drawn as elements with a fixed angle of 31° on the horizontal plane.

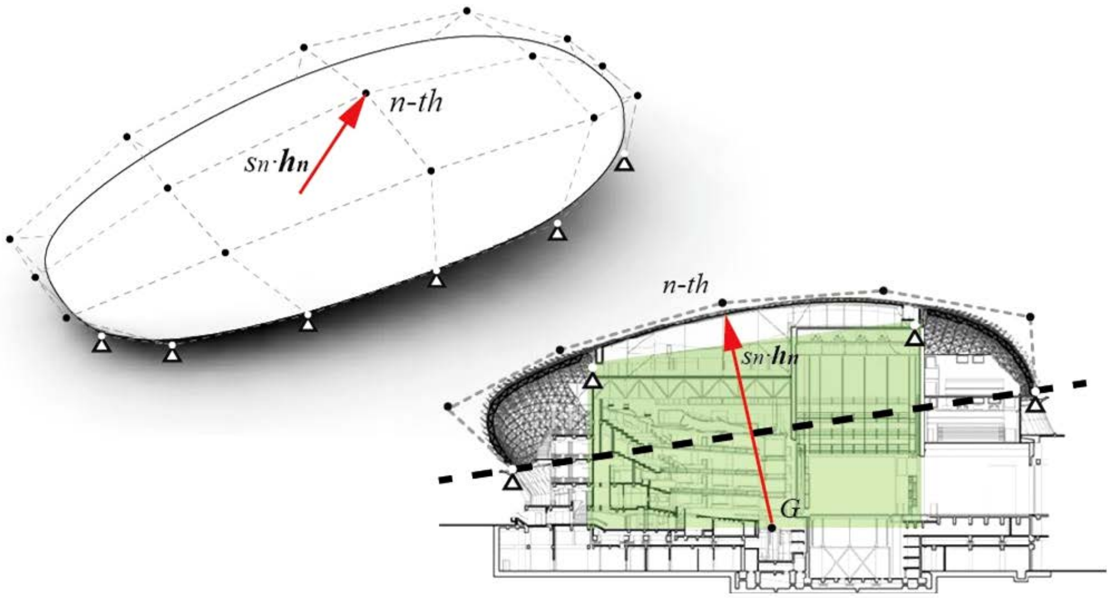

Figure 5. Esplanade parameterization. The control points *n-th* are governed by $s_n \cdot \boldsymbol{h_n}$. Top: parameterized geometry. Bottom: longitudinal section, the green geometry defines the control volume (free space). The black dashed line shows that the structure lies on a skewed plane.

The grid-shell boundary and 4 key points, in correspondence to existing beams, are constrained as shown in Figure 6. A gravitational load plus the self-weight have been applied and the maximum displacements have been calculated. The solar absorption has again been considered for the light analysis, as explained in the previous section.

The model is refined by setting a penalty function, *p*, related to the internal functionality of the building – the height of the cover roof cannot be decreased by more than a certain amount, therefore when the mesh vertexes interfere with a control volume, the fitness function has been increased by the number of interfering vertices. Several tentative solutions have been generated by this computational process of morphogenesis. The most relevant are shown in Figure 6.

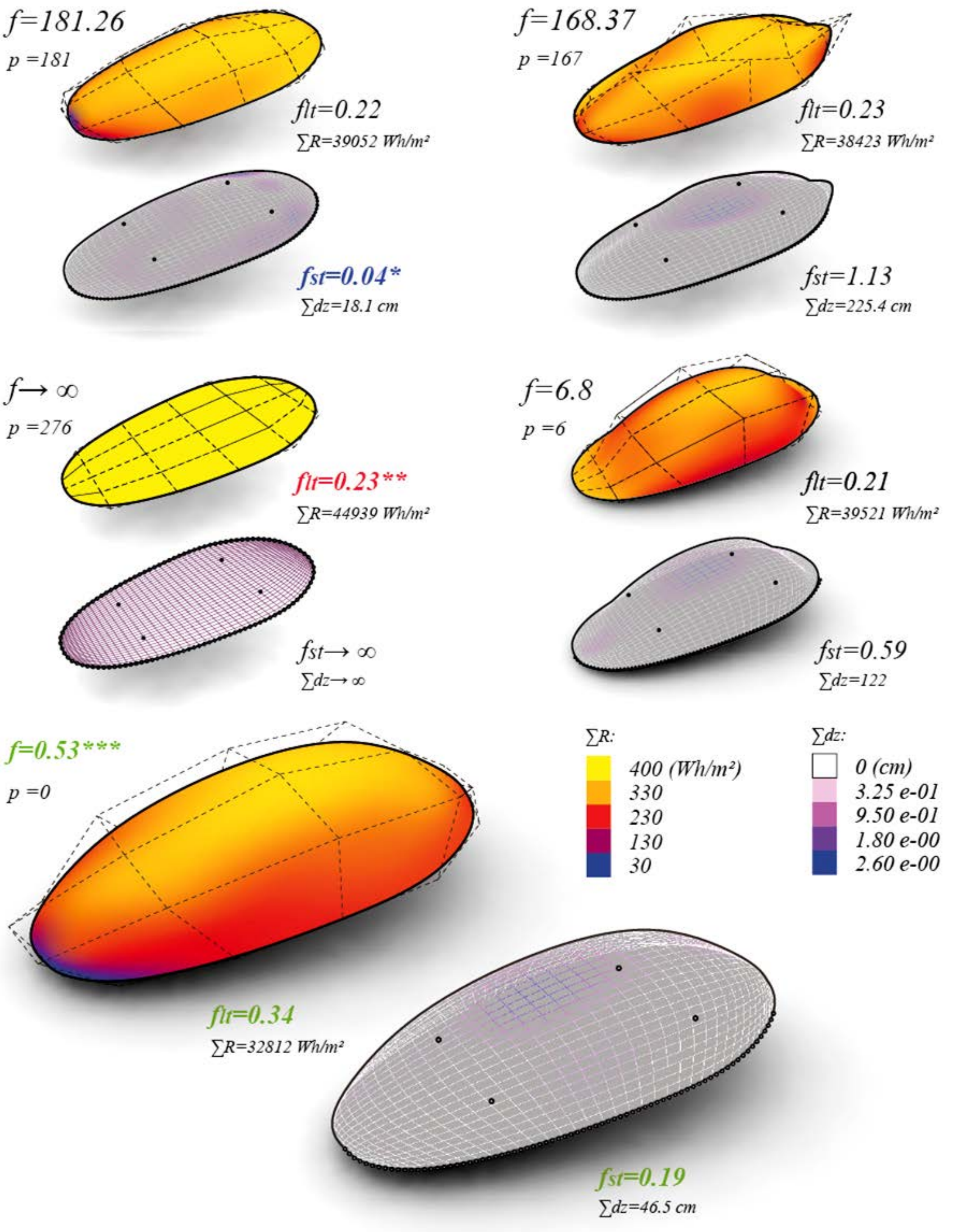

Figure 6. Some elements of the geometry population. Top left: the structural optimum* interferes with the control volume. Middle left: solar optimum**. Bottom: multi-objective optimum. Since 15 genes are processed, it is impossible to produce a graphic representation of the landscape solution domain.

5 CONCLUSIONS

A multi-objective optimization grid-shell problem has been presented in this paper. Structural behavior has been combined with the evaluation of light absorption in order to study how different and divergent performance criteria work together.

A simple benchmark has been used to introduce the concept of multi-objective optimization and to show how different fitness functions can lead to opposing optimal solutions. Furthermore, the analyses on the benchmark have shown that the exploration of the solution domain of the problem can be more important than reaching an actual optimum. For this reason, the benchmark has been set up with just two design variables in order to graphically map the fitness values on the solution domain – this could be considered as a 3D 'fitness landscape'.

Although further studies are needed to analytically identify the Pareto front of the problem, the actual strength of this work lies in in the simple way in which the multi-objective process has been set up – Rhinoceros, a NURBS 3D modeler has been used to manage the geometrical data, Grasshopper, a Rhinoceros plug-in, has been used to define the parametric model with the design variables of the problem, and Galapagos, the Genetic Algorithm implemented by Grasshopper, has been used as an optimization technique. Each step can easily be managed by an architectural designer and the overall process can be used for conceptual design purposes.

Finally, a real case study has been considered for the multi-objective optimization – the "Esplanade" in Singapore. The definition of the parametric model and performing the optimization procedure have shown the limits of simple and user-friendly tools when a more complex geometry is required.

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