

# Design tools for structural optimization

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## Abstract

Free-form computational modelling software places few limits on the imagination of the architectural designer. Engineers require new digital tools in order to realize these buildings and sculptures in an efficient and practicable manner. Collaboration between Buro Happold and Cambridge University has resulted in a toolbox of novel computational design tools which assist engineers and architects on projects with demanding free-form geometry; this paper presents two case studies which demonstrate just some of these tools. Outcomes have included: (a) development of new algorithms for true multi-objective optimization and for complex geometry synthesis (b) application of state of the art research to real projects, resulting in fully integrated optimization of structure, facade and internal environment.

**Keywords:** structural optimization, free-form geometry, multi-disciplinary design, multi-objective genetic algorithms, discrete differential calculus.

## 1. Introduction

Computational modelling software allows creation of increasingly complex building geometries. For any given project it can be a major challenge to synthesise an efficient structure whilst also meeting aesthetic, economic and construction requirements. It is widely recognised, both in industry and academia, that new digital design tools are needed to assist engineers e.g. Baker [2] and Coenders [3]. The focus of this paper is on the synthesis and optimization of lattice shell structures, for example the Saville Garden roof, shown in Figure 1.

Over the past four years a link has been established between Cambridge University Engineering Department and Buro Happold SMART (Software Modelling Analysis Research Technologies) team to conduct research in this area. The overall aim was to build a toolbox of novel computational design tools which assist engineers and architects on projects with demanding free-form geometry.



Figure 1: Saville Garden roof (courtesy of Warwick Sweeney).

## 2. Overview

There were two key objectives in the collaboration between Cambridge and Buro Happold:

- (i) Find existing state of the art optimization/geometry methods and implement them in a practical and user-friendly manner.
- (ii) Develop new techniques which address gaps in the literature relating to multi-disciplinary design optimization of structures with free-form geometry.

Specific outcomes and tools discussed in this paper include:

- 1) Application of fast structural optimization algorithms to new practical situations, through the development of the SMART Sizer application, based on virtual work methods proposed by Baker [1].
- 2) Implementation of user-friendly tools for generating complex grid geometries on free-form surfaces, in SMART Form Rhino plug-in. This includes both techniques for creation of primary structure and for cladding/facades.
- 3) Creation of novel methods for grid shell synthesis and optimization. These new algorithms were constructed by drawing on, and further developing, research from aerospace composites, discrete differential geometry and multi-objective evolutionary optimization. Technical details have been given in previous IASS conferences and journal by the authors (Winslow et al. [7, 8]).

These innovative tools allow ever more complex structural geometries to be generated, analysed and manipulated. They facilitate much greater architectural freedom and exploration throughout the whole design process, even for unusual free-form surfaces. This paper now demonstrates the successful application of methods from the toolbox to two case studies: Elephant House roof, using (3), and Perforated Museum roof, using (1) and (2).

### 3. Elephant House roof

#### 3.1. Problem definition

The Elephant House roof surface to be constructed is shown in Figure 2(a) and is approximately 100 m by 80 m. The concept shown in Figure 2 was a competition bid for a new elephant house at Zurich Zoo. The surface is highly curved in places (around tops of columns), will be covered with a 'green' sedum bio-diversity roof and contains a number of holes through which people can view the elephants, Figure 2(c).

It was initially proposed, by the project engineer, that the grid layout should be a vertical projection from the  $x$ - $y$  plane and its topology is based upon two primary sets of rods with triangulation along both diagonals as shown schematically in Figure 2(b). This case study considers varying rod orientations on the surface in order to minimize three objectives:

- (1) Deflection under self-weight (serviceability criterion).
- (2) Maximum member stress due to wind + self-weight (ultimate limit state criterion).
- (3) Total mass of structure.

Note that buckling load is also important, but initial investigations showed that this closely correlates with objective (2), so it is not necessary to consider it as a separate objective.

The multi-objective grid layout optimization method proposed and developed by Winslow [8, 9] is used to tackle this problem (i.e. the third bullet point from Section 2). This new tool allows exploration of a much wider range of grid layouts on any free-form surface. Although the initial case study surface is a NURBS Rhino model, the optimization tool has its own bespoke triangulated surface mesh geometry engine. This facilitates the use of highly sophisticated discrete mathematical techniques e.g. Ray [5], for robust, automated grid layout synthesis.

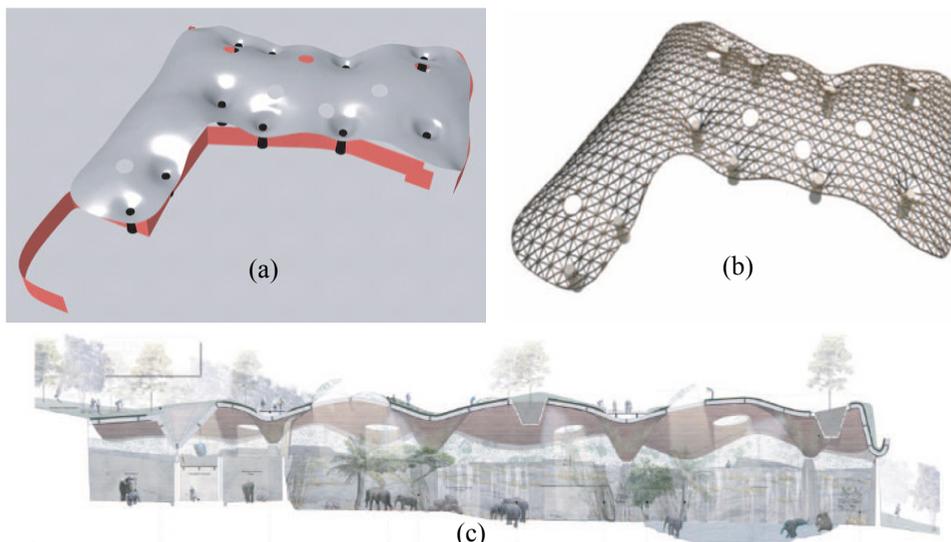


Figure 2: Elephant House problem definition. (a) Given surface. (b) Initially proposed grid layout. (c) Artist's impression

Twenty one design variables are used:

- Two rod angles at each of the 9 design points
- Rod spacing
- Cross section size for primary rods (chosen from a list of 6 different steel tubes)
- Cross section size for secondary rods (chosen from a list of 6 different steel tubes)

### 3.2. Design tool initialization

The optimization problem is initialized by manually picking a number of design points on the surface, at which the directions of the two primary sets of rods are defined; see Figure 3(a). Note that the directions of the red and green arrows show primary rod orientations; in this figure they are arbitrarily defined but it is easy to see that changing the directions of these arrows will alter the rod paths; hence the structural layout can be optimized. The user also picks a number of fixed points which specify the location of supporting columns.

A complete, smooth grid is then automatically generated from these sparsely defined rod directions using discrete differential geometry techniques (Winslow [8]). An example of the primary rod paths (which represent a re-parameterization of the surface) is shown in Figure 3(b). Triangulating rods and locally convergent rods around tops of columns are then easily added, and a complete FE model is created. Any optimization algorithm could then be used to change the directions of the red and green arrows in response to the structural performance. Figure 4 gives an overview of how the grid layout is automatically optimized over 200 generations using a multi-objective genetic algorithm to simultaneously minimize the 3 objectives, with no need for an aggregate objective function.

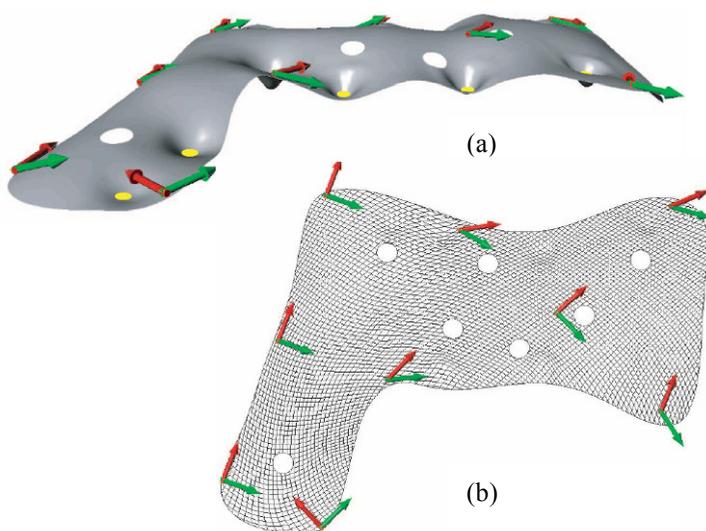


Figure 3: Rod directions defined sparsely at design points. (a) Design points on surface (perspective view). (b) Complete grid fitted smoothly to red and green direction arrows (plan view).

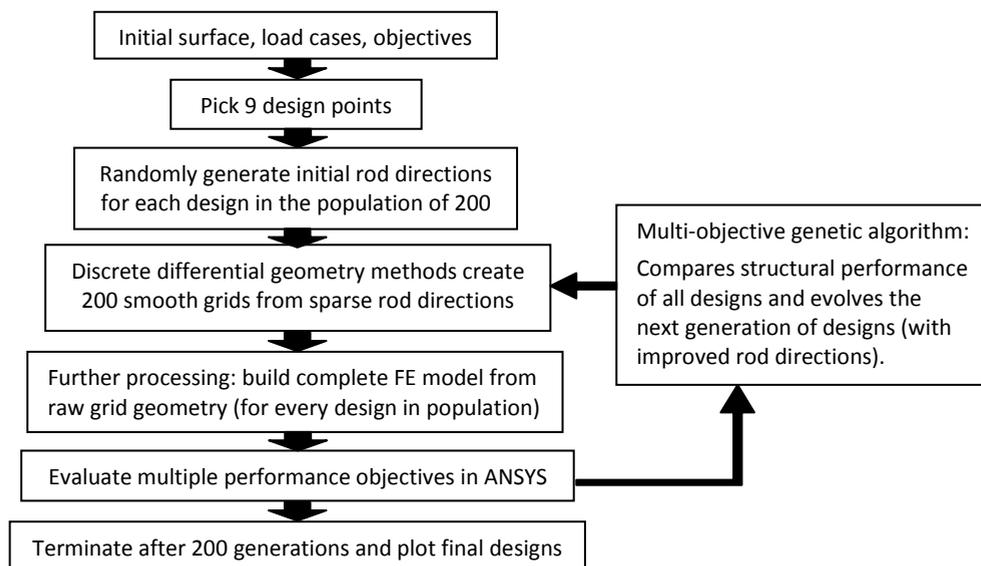


Figure 4: Optimization tool flow chart.

### 3.3. Results

A geometrical quality measure (GQ) is introduced to aid the engineer in choosing a good design from the final population of 200 designs. Lattice structures in which all rods are of similar length are often considered to have good aesthetics (e.g. equal mesh net grids are very popular). Therefore designs in the final population will be sorted using the normalized standard deviation of rod lengths,  $GQ = s / \mu$ , where  $\mu$  = mean rod length,  $s$  = standard deviation of rod length. 13 designs have a much better geometrical quality than the other 187 designs; results are shown in Figure 5. Comparing this reduced final population with the best designs from the initial population shows that deflection can be reduced by 60% (for the same mass) or stress reduced by 20% (also for same mass). Figures 6, 7 and 8 show two designs from the final population; visually diverse with excellent structural behaviour.

### 3.4. Discussion

This tool allows creation of optimized grid layouts during early design stages; these can be now be taken forward to detailed design e.g. buckling checks, and individual member size optimization. The new design tool allows the designer to easily consider a much wider variety of grid layouts, and is no longer inhibited or slowed down by handling the free-form geometry. The multi-objective nature means that the trade-offs and merits of the different performance criteria can be understood and explored much more easily. The novel use of discrete differential geometry ensures that the grid layouts are smoothly curving, rational and practicable. A variant of the tool involves utilizing the geometry engine for user-guided synthesis of a complete grid on a free-form surface. The architect/engineer can directly create grids as per Figure 3 by manually specifying sparse rod directions (rather than using a genetic algorithm); details are given in Winslow [9].

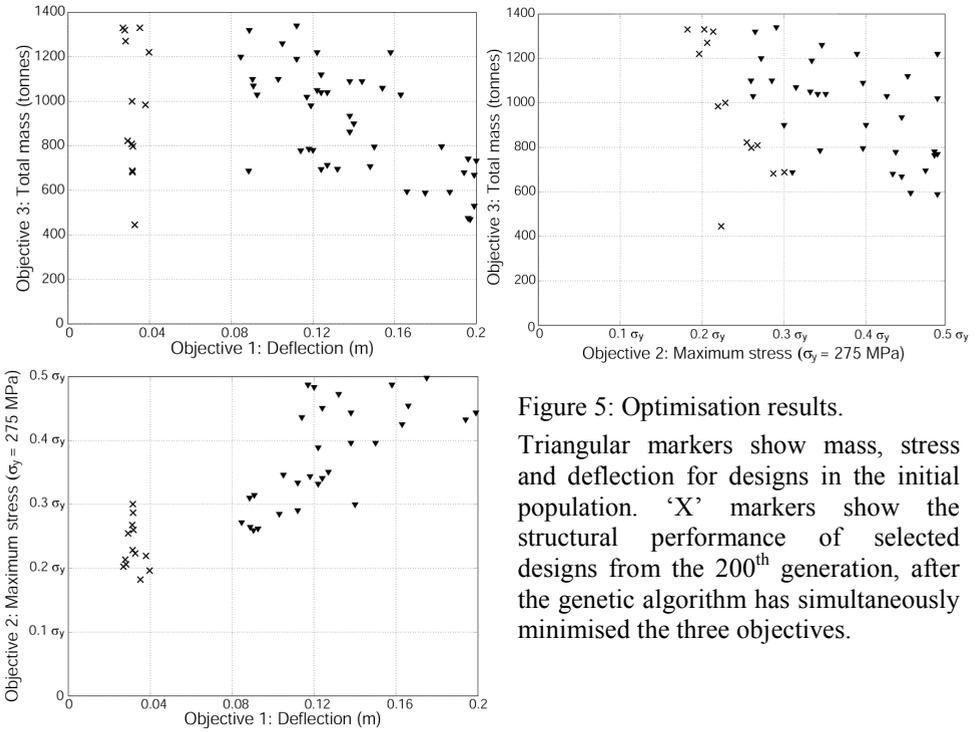
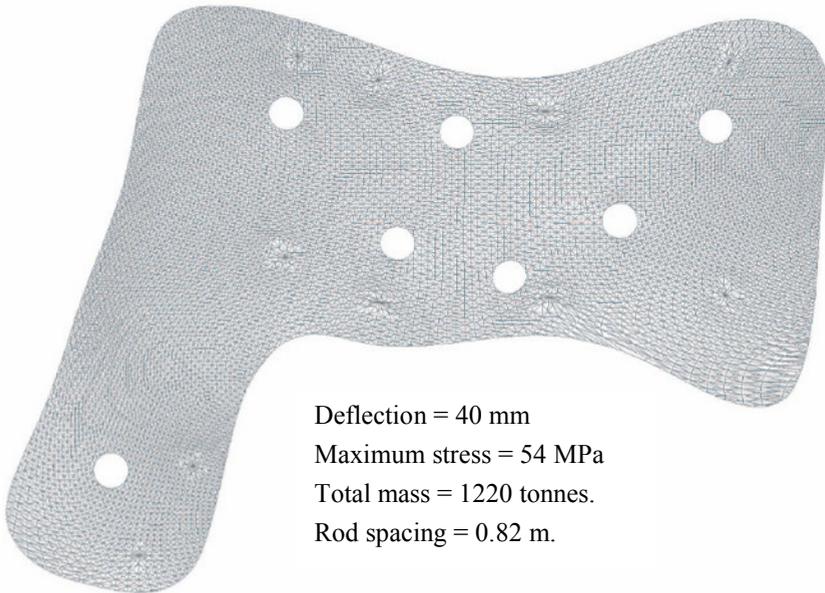


Figure 5: Optimisation results.  
 Triangular markers show mass, stress and deflection for designs in the initial population. 'X' markers show the structural performance of selected designs from the 200<sup>th</sup> generation, after the genetic algorithm has simultaneously minimised the three objectives.



Deflection = 40 mm  
 Maximum stress = 54 MPa  
 Total mass = 1220 tonnes.  
 Rod spacing = 0.82 m.

Figure 6: Optimized grid layout A

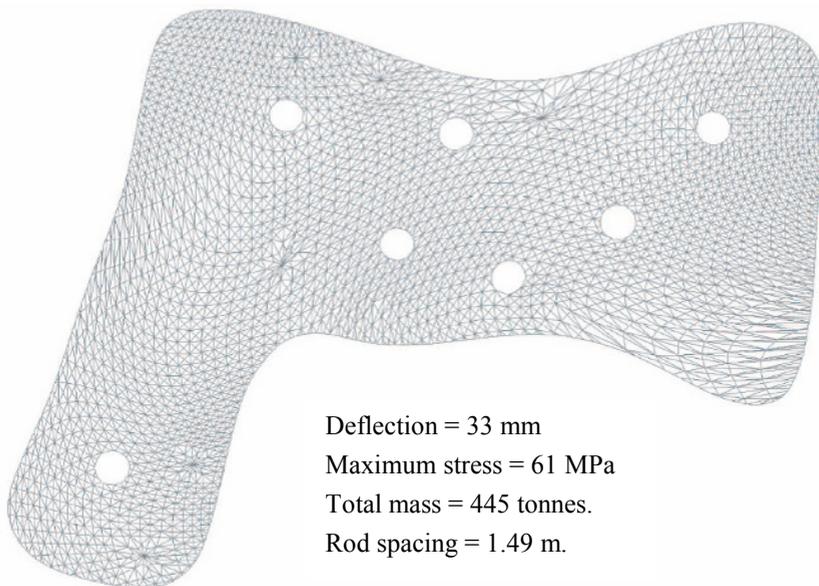


Figure 7: Optimized grid layout B



Figure 8: Rendered view for optimized grid A

## 4. Perforated Museum roof

### 4.1. Overview

The image in Figure 9 shows a domed roof forming the basis for a prominent international museum. The team have been developing the tools to enable automated generation and control of this elaborate structure.

The shallow, 180m diameter dome, supported at only four points around its perimeter, is constructed as a steel space frame under a complex perforated multi-layer façade. It is through this structure that the lighting and solar environment will be closely controlled to improve the local microclimate whilst creating stunning light dappling effects below. The complex nature of this concept means that the geometry of the primary structure and cladding pattern has direct implications on a number of the project design team disciplines. Working with architecture, façades, structures, lighting and building environment teams, the aim has been to integrate the generation and optimization of the complex dome geometry into the design process.

The aim of this work has been to allow parametric generation of the full dome and cladding geometry enabling complete and detailed control over the modelling process. This has made it possible to make subtle geometrical variations affecting the dome opacity based on computational and physical scale model lighting studies. This process has allowed full integration of the complex architectural aesthetic with the strict environmental and structural engineering requirements (see flowchart in Figure 12).

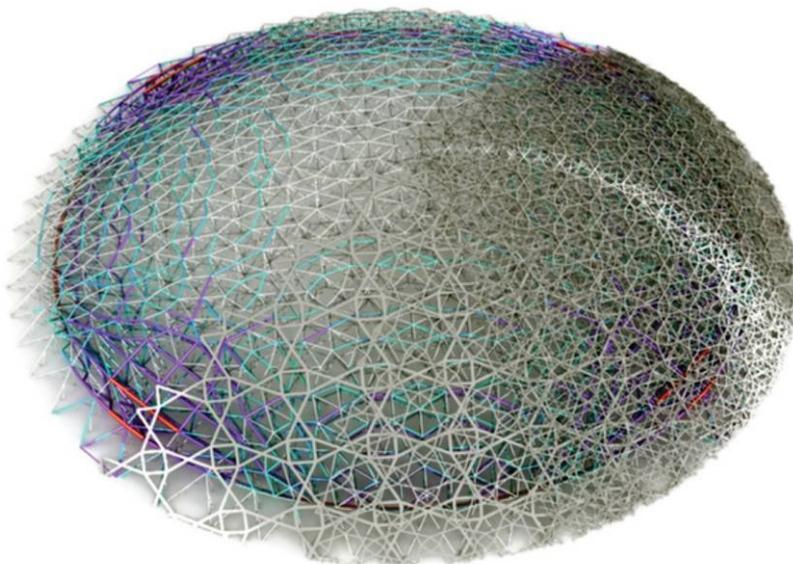
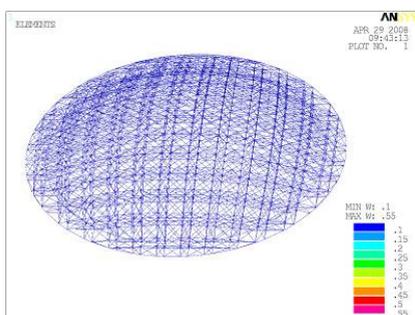


Figure 9: Complex space frame structure with multilayered perforated cladding system

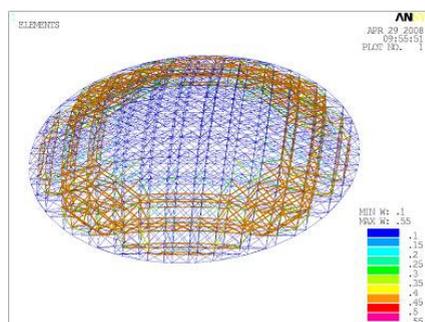
## 4.2. Structural Optimization

The design team have used SMART Sizer, our innovative one-step optimization tool which derives individual member sizes for any structure under a given load case and boundary conditions developed from virtual work methods e.g. Baker [1]. Using these tools a fully automated design optimization exercise has been carried out on the dome, using Rhino 3D, Ansys and SMART Sizer, leading to major cost savings while achieving the deflection, stress and buckling criteria. Due to the high redundancy of the space frame, an iterative variation of our one-step optimization method was implemented taking into account the changes of the load path as the section sizes of the model are changed.

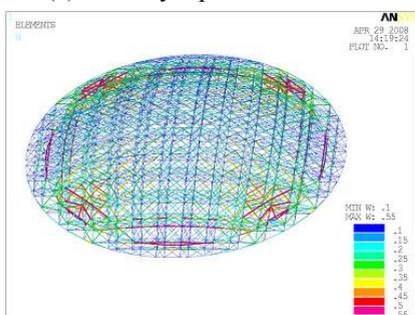
The analysis plots in Figure 10 illustrate the variation of structural section sizes throughout the dome structure. Starting from an initial model with all members set to a minimum size, the structure is first optimized for deflection. This is critical to limit the maximum deflection at the lip of the dome mid span between supports. In contrast Figure 10(c) shows the optimally resized structural sections for strength only. Here there is a requirement for high strength members around the supports and increased member sizes in the central compression zone where the members' effective length reduces their permissible stress.



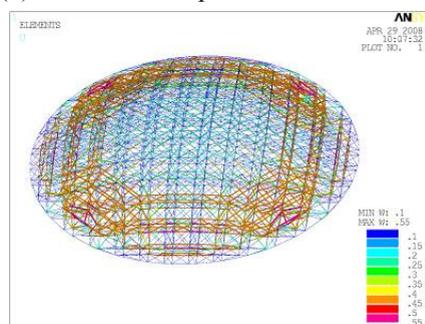
(a): initially equal section sizes



(b): section sizes optimized for deflection



(c): section sizes optimized for stress



(d): section sizes optimized for both deflection and stress

Figure 10: Structural optimization of the dome enables effective distribution of material

The final structural solution, satisfying both stiffness and strength criteria, was achieved by optimizing for deflection whilst incorporating a robust member check for allowable stress and local buckling. In addition a sensitivity analysis, optimizing for a range of deflections, 300–600mm, enabled a trade-off between deflection and minimum weight to be achieved.

The allowable members are selected from a finite list of standard section sizes, so no post rationalization is required. The initial optimization was performed for self weight, cladding and maintenance loading, the governing load case. The design process then consisted of an in-depth detailed structural analysis and series of additional optimization iterations ensuring compliance for multiple load cases.

This approach enabled a dramatic reduction in steel self-weight during conceptual and design development, however the real benefit of the tool was realized in the increased efficiency of the design process allowing rapid exploration of numerous design options.

### 2.3. Cladding Optimization

The team has adapted their in-house modelling tool SMART Form which allows digital prototyping of complex curved forms, by splitting them into a multi-dimensional grid. The tool then enables geometrical optimization for architectural, fabrication, and environmental considerations. The software works within Rhino 3D environment allowing it to be readily used on any generic geometrical form. At the same time the code is easily adaptable to work with other 3D CAD packages.

For this project SMART Form has been extended to enable overlaying of any bespoke unit-cell pattern, together with the ability to generate defined pattern parameters based on input from reversed engineering lighting simulation data. The result is full parametric control over the generation of the cladding geometry (Figure 11). The geometry can be sent directly for 3D prototyping or for further lighting/environment simulations or validation studies.

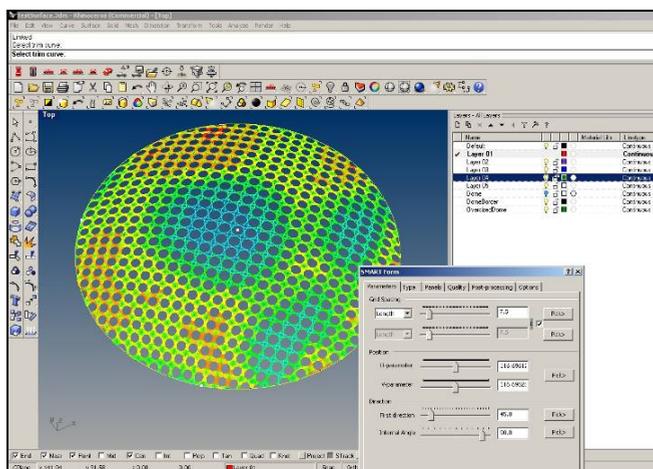


Figure 11: Parametric control of façade element widths defining variable light translucency

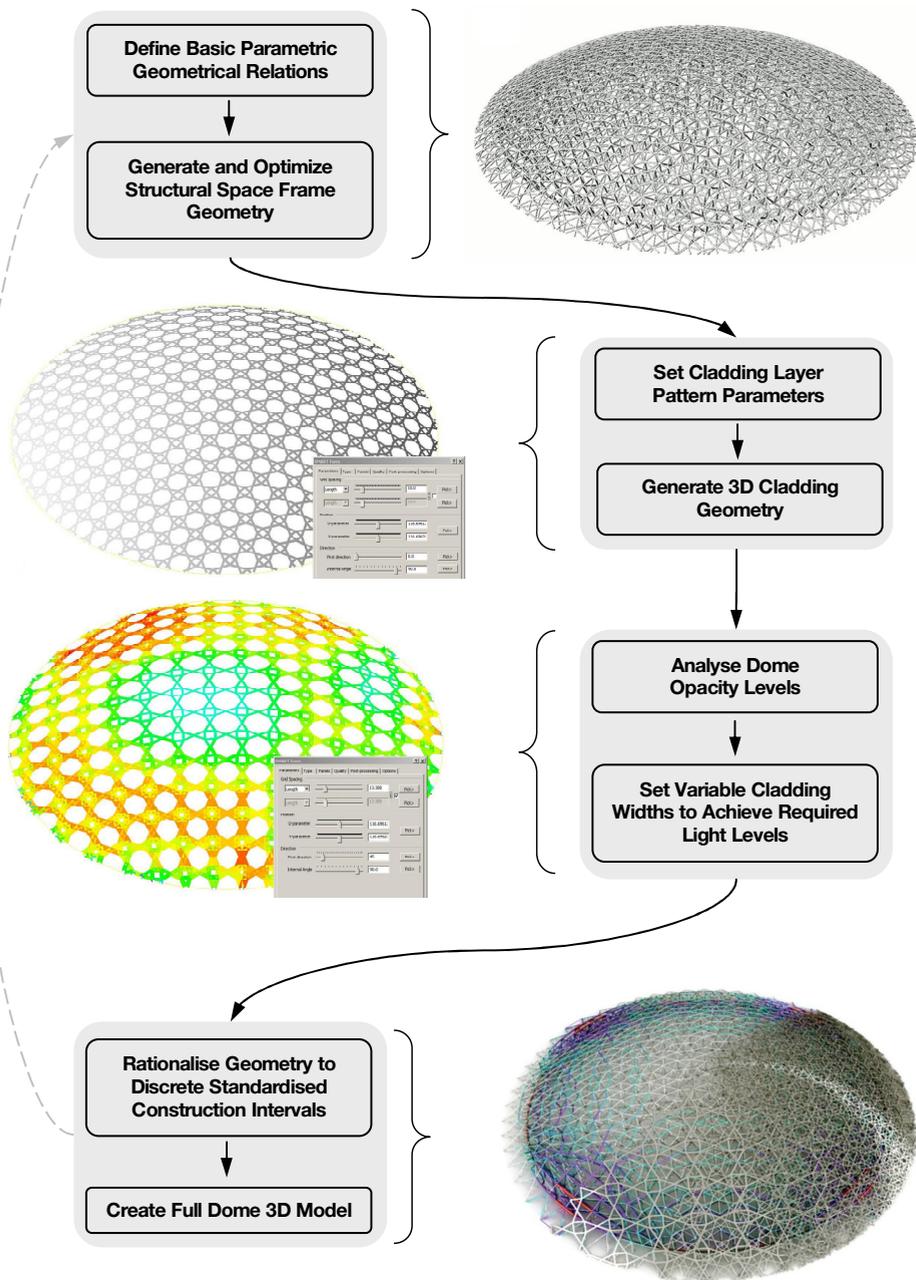


Figure 12: Illustration of the automated pattern generation process and translucency analysis.

## 5. Summary

The two case studies in this paper have shown just some of the novel tools developed during this collaborative project. Specifically this has included demonstration of:

- State of the art techniques for creating and exploring highly complex but practicable grid geometries, and for conducting true multi-objective optimization - in ways not previously possible for free-form structures.
- Advanced SMART Form and SMART Sizer tools, developed from research methods, which enable integrated optimization of structural and environmental performance in a rapid, user-friendly manner.

Overall, the project has helped to build up a set of innovative tools enabling simple solutions to complex problems.

## 6. Acknowledgements

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