Proceedings of the IASS Annual Symposium 2017
"Interfaces: architecture . engineering . science"
September 25 - 28th, 2017, Hamburg, Germany
Annette Bögle, Manfred Grohmann (eds.)

Continuous to discrete: computational performative design and search of shell structures

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Abstract

This research assesses structural and daylighting performance of perforated shell structures. By employing computational design tools and performance assessment methodologies, an array of generated topologies of perforated shell structures spanning the two extremes is studied. These generated topologies are coupled with structural and daylighting performance criteria to allow a performance-oriented exploration of the design space. ParaGen is used to automate the cycle of generation and evaluation. ParaGen is a method that uses a genetic algorithm (GA) to search for well performing geometric solutions to architectural engineering problems. By using ParaGen, the quantitative performance results are stored in a SQL database, accessible through an online website. The significance of this study is twofold: first, it studies a spectrum of generated forms of well-established structural typologies with perforations; and second, it couples structural and daylighting performance with geometry towards computational performance-based design and search of well performing alternatives. The results of the study contribute to the area of computational design, multi-objective design exploration as well as shell structures.

Keywords: Computational design, computational search, shell structures, concrete shells, topology, structural performance, daylighting performance

1. Introduction

Robert le Ricolais's influential structural engineering work from the 1960's was guided by his belief that "the art of structure is where to put holes"(Pennsylvania [14]). The paradox is that the removal of material that weakens a structure also makes it lighter, thus makes it more efficient. In the case of continuous shell structures, having holes does not stop the thin curved surface from being a shell. But the perforations in a continuous shell do provide an opportunity for introducing daylight into the space. On the other hand, grid shell structures are formed by intersecting members which provide the opportunity to design openings which admit daylight into the space. A colander and a sieve are the commonly used analogies to compare continuous shells and grid shells. Where a colander has a continuous surface with a relatively small areas removed, a sieve is a surface made from a large number of initially straight wires which are woven into a flat sheet and then bent into a hemisphere (Adriaenssens et al.[1]). From a topological standpoint, a continuous shell can be perforated until it becomes a grid shell. Therefore, the array of shell topologies between a continuous and a grid shell is certainly worth investigation.

An instance of a designed and built perforated thin shell structure is the roof of the Fronton Recoletos (1935), created by Eduardo Torroja (1899-1961), the brilliant Spanish engineer. The shell structure was destroyed during the Spanish Civil War (Mungan and Abel [11]), but once covered a 55 by 32.5 meter space designed for a ball game. The perforations allowed for natural daylight. A thin concrete shell was designed, and in those areas where skylights were needed, the shell was replaced by a triangulated structure designed for the insertion of glass panels (Figure1) (Lozano-Galant and Payá-Zaforteza [10]).

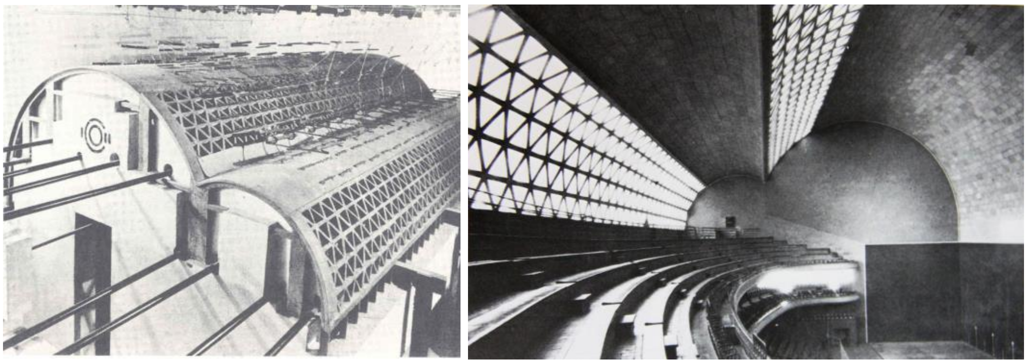

Figure 1: Thin shell with triangulated openings designed for Fronton Recoletos

Looking at the history of shell structures in general and from the beginning of the 20th century, designers started to see the potentials offered by the plastic qualities of liquid concrete. Kirovski et al. (2014) points out that the first wave of the era of thin shells from 1922 to 1965 is regarded as the golden age of thin shell structures (Krivoshapko et al. [9]). Remo Pedreschi (2008) describes that the majority of the designs used concrete as a ‘tectonic compact’, where its qualities go beyond purely structural to become shelter and skin. According to Pedreschi, Angerer was the person who proposed “surface structures” as a new classification of these structures to differentiate them from the historical classification of the solid or the skeleton and skin (Pedreschi [13]). Giles (2005) describes shells as more than a general surface that describes three-dimensional space as a continuum. “The skin of a shell has rigidity, therefore it is more than a simple poly-surface graphic, it is a surface that possesses intelligence based on material and geometric properties, which could include texture, transparency and climatic performance” (Giles [7]).

However, during the last decades, and according to Jörg Schlaich, concrete shells lost more ground to cable nets, textile membranes and steel grids (Adriaenssens et al. [1]). Sasaki lists the reasons for reduced construction of reinforced concrete structures nowadays, as “scarcity of skilled workers, rising prices for formwork, cost and schedule challenges, the inefficiency of on-site fabrication, large deformations, deteriorations in the concrete, and a transition to steel grid shell to satisfy new demands” (Sasaki [17]).

Recently, and in the half-century following the decline of concrete shell construction, there is a renewed interest in these structures. The reason is threefold. Firstly, there is a rise of a new trend in architecture towards expressing informal three-dimensional shapes that possess free, complex, and organic characteristics towards a contemporary shell design. Secondly, material developments lead to availability of lightweight, thin reinforcement materials for concrete on one hand, and more efficient concrete mixes on the other hand. And thirdly, CAM (Computer Aided Manufacturing) methods have evolved as an aid in constructing these complex forms.

This research builds on the increased interest in shell forms and in particular free form shell structures that may be optimized on functional performance. Performance-based design, in which building performance becomes a guiding design principle, emerged as a design paradigm due to the emphasis on sustainability as a defining socio-economic issue, and due to the recent developments in technology and cultural theory (Koleravic [8]). In performance-based design, the emphasis shifts from the “product” to the “process” of form generation based on performative strategies of design. Simulation is one of the influential concepts of performance-based design for analysis, which can also redefine “performative design” when integrated with generation (Oxman and Oxman [12]). Past researchers have employed computational design strategies to optimize shell structures regarding their structural performance (Pugnale and Sassone 15]). Assessing the structural and daylighting performance of perforated shells simultaneously has also been conducted on a case study (Emami [4]). However, past research has not demonstrated a comparison between the performances of the two ends of the continuum of shell structures, nor the topologies generated in between. This research study is focused on the performative design and exploration of perforated shell structures. It investigates a spectrum of generated forms of shell typologies, considering their coupled structural and daylighting performance criteria.

2. Methodology

A parametric model is built to demonstrate the transition of a dome into a vault and then a saddle. Change in the curvature of the edge curves allows the parametric model to generate a range of geometries, with positive, zero and negative Gaussian curvature (Figure. 2). According to Blaauwendraad et al (2014), if point A is defined on a smooth surface, there will be a tangent plane at that point, where the normal to the surface is defined to be normal to the tangent plane. There are an infinitely many plane curves at point A, but one of them has a minimum curvature and another has a maximum curvature. These two plane curves are called the “principal sections”, and their curvatures are called the “principal curvatures” denoted by k_1 and k_2. The product of the two principal curvatures, $k_g = k_1 * k_2$, is called the Gaussian curvature of the surface. The Gaussian curvature can be positive, negative or zero. If it is positive, k_1 and k_2 are having the same sign and the resultant surface is synclastic or a dome-shaped surface. If the Gaussian curvature is negative, k_1 and k_2 have opposite signs, and the surface is anticlastic or a saddle-shaped surface. If either of k_1 or k_2 is zero, their product is zero thus the surface has a single curvature or is vault-shaped (Blaauwendraad and Hoefakker [2]).

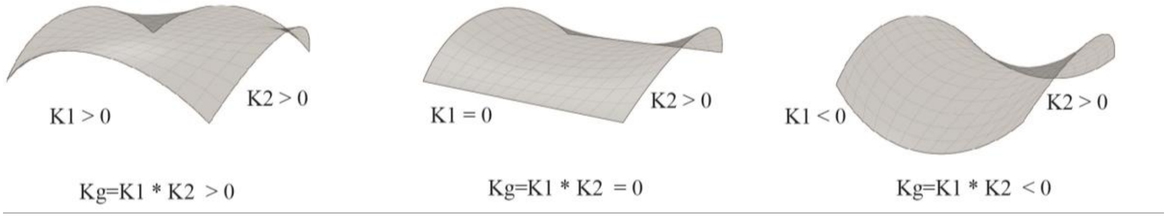

Figure 2: synclastic, single curvature, and anticlastic forms with a positive, zero and negative Gaussian curvature

The parametric model also demonstrates the transition of a continuous shell into a grid shell. Grasshopper, a visual programming environment integrated with Rhino NURBS modeling software has been employed as the modeling tool. Once the edge curves are generated, a surface is constructed and RhinoMembrane plugin in Grasshopper is used for membrane form finding. Afterward, Weaverbird, a plugin for Grasshopper, is used for triangulating the mesh. The mapped triangulation is the basis for subtracting perforations. A python algorithm systematically removes apertures from the shell and makes it perforated. The geometry generation workflow is demonstrated in Figure 3.

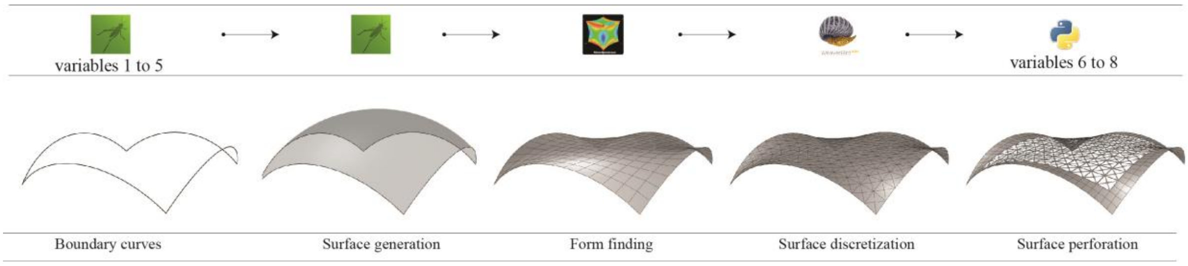

Figure 3: The steps for generating the geometry in Rhino

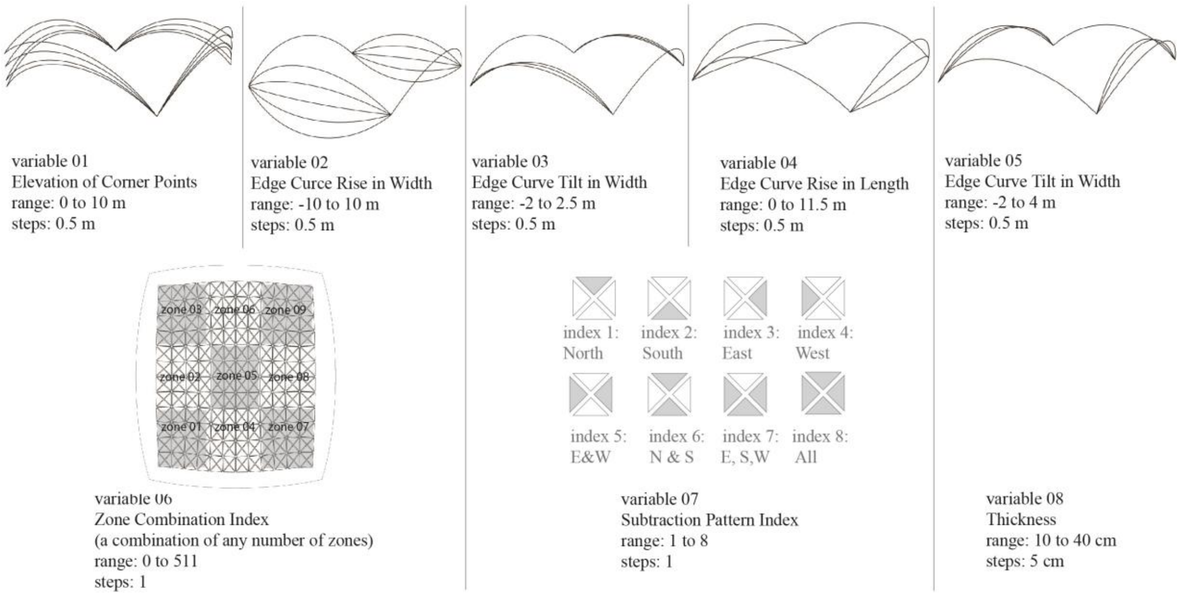

Figure 4: The variables that change the parametric geometry in Grasshopper and with related plugins

There are a total of 8 variables that are implemented in the parametric model that drive the generated geometry. Five variables change the global geometry by changing the boundary curves, and three variables change the local geometry by defining the location and percentage of perforations as well as changing the shell thickness (Figure 4).

The strategy for subtracting the apertures from the mapped triangulation is twofold. Firstly, a margin is isolated along the outer boundary of the mesh where no meshes are subtracted. This approach is essential for later structural analysis that requires a solid edge beam. Secondly, the python algorithm divides the remaining triangulated meshes into nine zones. Later, the algorithm chooses any number of zones and combines them together (equation 1). In each combination, the order of zones doesn’t matter and the combinations with same items in different orders are not allowed to repeat. As an example, if only one zone is to be chosen, stated as “choose 1 from 9”, there are nine possible combinations including “zone 1 or zone 2 or… zone 9” (equation 2), whereas if nine zones are to be chosen, there is only one possible combination including “zone 1 and zone 2 and … zone 9” (equation 3). The number of total zone combinations are calculated as 511 (equation 4). In the extreme case where all apertures are subtracted, an open grid mesh is retrieved.

$$C(n,r)=\frac{n!}{(r!(n-r)!)} \tag{1}$$

$$C(9,1)=\frac{9!}{(1!(9-1)!)}=9 \tag{2}$$

$$C(9,9)=\frac{9!}{(9!(9-9)!)}=1 \tag{3}$$

$$C(9,0)+C(9,1)+C(9,2)+C(9,3)+C(9,4)+C(9,5)+C(9,6)+C(9,7)+C(9,8)+C(9,9)=511 \tag{4}$$

Once any number of zones are combined, another python algorithm maps a subtraction pattern onto the grid in order to control subtractions at a micro level. Not all the apertures of the selected zone are subtracted, but a 25%, 50%, 75% or 100% perforation ratio facing various orientations can be selected.

After the geometry is generated, the structural, daylighting and energy performance are assessed. Karamba, DIVA and Archsim in Grasshopper are used for structural, daylighting and energy performance assessments respectively. Karamba is a Finite Element Method (FEM) simulation engine, whereas DIVA and Archsim use Radiance and Energy Plus engines respectively. Ghowl, a plugin for Grasshoper, is used to read and write the input and output data to an excel file. ParaGen is used to automate the cycle of generation and evaluation by using AutoHotkey to script the sequence of steps. ParaGen is a method that uses a genetic algorithm (GA) to search for well performing geometric solutions to architectural engineering problems (von Buelow [18]). By using ParaGen, the quantitative performance results as well as the qualitative renderings of the solutions are stored in a SQL database, accessible through an online website. The workflow is illustrated in Figure 5.

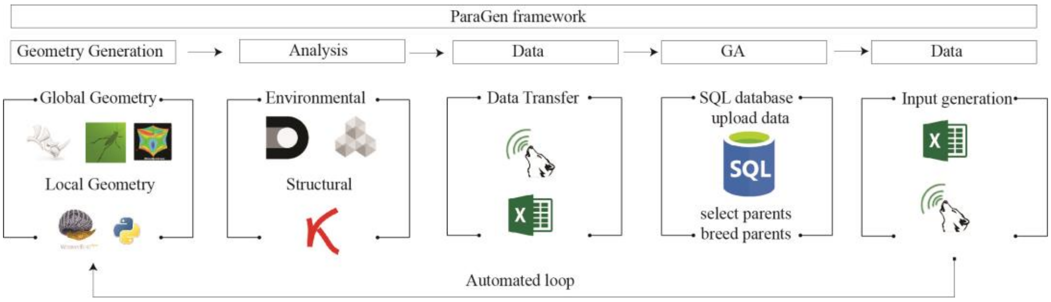

Figure 5: The automated ParaGen workflow

2.1. Structural analysis

Karamba is used for structural analysis. The corners of the shell are chamfered before the supports are defined. This reduces formation of local stresses at the support and transfers load to the ground on a wider support. The movement and rotation of the supports is restricted in x, y and z directions. Concrete is used for the shell as the main material. The material properties are given in Table 1.

Table 1: material properties

Elastic Modulus (E) [KN/cm^2]	Shear Modulus (G) [KN/cm^2]	Specific weight (Gamma) [KN/m^3]	Coefficient of thermal expansion (alpha T) [1/C°]	Yield Strength (f_y) [KN/cm^2]
2600	1080	23.52	0.00001	3

A uniform load of 1 KN/m^2 is applied to the shell in the negative z direction (equation 5). This load is adjusted once the shell is perforated. The equation for adjusting the load is described below.

$$Load = \frac{Area_{solidShell}}{Area_{perforatedShell}} \times 1[KN/m^2] \tag{5}$$

As an instance, a 1 KN/m^2 load is applied to a solid shell of any shape, but if the same shell is 50% perforated, then the load will be doubled (equation 6). The load adjustment is necessary since the glazing are not loaded, towards comparing different shells under the same loading conditions.

$$Load\ For\ 50\%\ Perforated\ Shell = \frac{1}{0.5} * 1[KN/m^2] = 2[KN/m^2] \tag{6}$$

Dead load is also calculated and applied to the shell. The weight of the shell is calculated based on the solid parts only whereas holes are simply zero weight. In other words, the weight of the glazing on the shell is not included in the dead load, which gives an approximation of the self-weight of the shells.

Once the material, supports and load are applied to the shell, the maximum displacement and the von Mises stress levels are analyzed in Karamba. The aforementioned steps are illustrated in Figure 6.

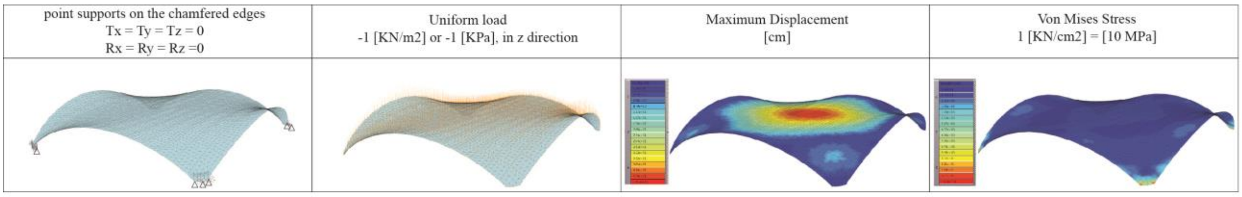

Figure 6: boundary conditions and structural analysis

It should be noted that although maximum displacement is calculated for serviceability conditions, maximum von Mises is not considered for the strength criteria. Instead, a proportional statistical distribution analysis is carried out using the von Mises stress levels of all the nodes, where only von Mises stress at the third quartile (Q_3) is considered. In statistics, the quartiles of a ranked set of data are described as three points that divide the data set into four equal groups. The third quartile is the middle value between the median and the highest value of the data, meaning that 75% of the data lie below it. This approach acknowledges the fact that the nodes that are subject to extreme stresses significantly higher compared to the majority of the remaining nodes are not the base line for designing the shell. It averages out the maximum stresses, assuming that a degree of redistribution will take place in reality, whereas the analysis software tends to predict extremely high stresses at points of discontinuity, which is also dependent on the mesh configuration used by the analysis algorithm. These highly localized extreme stresses are also considered local effects that do not impact on the sizing criteria for the shell as a whole.

2.2. Daylighting and energy simulations

DIVA for Rhino and Archsim are used for daylighting and energy analysis respectively. A 50 m by 60 m floor plan is consistent among all shell typologies and topologies. A 1 m by 1 m horizontal grid is defined at the height of 0.9 meters from the ground to measure daylight illumination. The surrounding walls, floor, ceiling and glazing are defined as a 35% reflectance Outside Facade, 20% reflectance Generic Floor, 80% reflectance Generic Ceiling and 20% reflectance Generic Translucent Panel. It should be noted that there are no external nor internal shading devices modeled, therefore, the glazing is set to translucent to mitigate the effect of glare while providing natural daylight for the space. The Radiance parameters are set as default which are -aa .15 -ab 2 -ad 512 -ar 256 -as 128 -dr 2 -ds .2 -lr 6 -lw .004 -dj 0 -lr 6 -sj 1 -st 0.15. The location is set to Boston (42.36º N, 71.05º W) and the weather data for Boston Logan Airport is downloaded from the Energy Plus website[i].

Once the daylighting analysis is completed, a daylighting schedule is retrieved which feeds into the energy analysis setup. In other words, the times of the year where the required light levels are being met by daylight alone will be excluded from the energy analysis schedule which ultimately reduce the electricity energy needed for lighting. Custom concrete materials are added to the Archsim library for various concrete thicknesses which result in different U-values and thus differing heat transfer rates. In the energy analysis set up, the floor and walls are considered adiabatic, thus the shell roof is the only surface that transfers heat. This strategy will eliminate the difference between the surface areas of different walls due to various alternatively formed shell curvatures (Figure 7).

Figure 7: different shell curvatures affect the surface area of the surrounding walls, thus the walls are modeled adiabatic

According to the three performance categories expressed as daylight availability, visual comfort, and thermal loads (Reinhart and Wienold [16]) for environmental analysis, the metrics presented in Table 2 are selected for daylighting availability, visual comfort performance and energy assessment. It should be noted that the target required light level of 300 lux has been selected. In addition, since the annual Daylight Glare Probability (DGP) simulation is computationally expensive, a point-in-time DGP is calculated for noon at June 21st.

Table 2: Metrics for assessing the daylighting, glare and energy loads

Criteria	Metric
$sDA_{300/50\%}$>50%	Spatial Daylight Autonomy of 300 lux for at least 50% of the year should be met by 50% of the surface area
$DA_{oversupply}$ <= 5% of the year	The maximum amount of DA is 10 times more than the target daylight: DA_{max}= 10 * DA = 10 * 300 lux = 3000 lux.3000 lux is considered as oversupply and should not occur more than 5% of the year.
DGP < 0.04	Daylight Glare Probability should not be intolerable or disturbing
[Kw/hr]	Lighting, cooling and heating energy loads

3. Multi-objective design space exploration: coupled analysis

The design space can be explored interactively through a webpage that shows the renderings of the alternatives (Figure 8). Each solution can be scrutinized more by clicking on it to read its detailed design parameters and performance criteria in both structural and daylighting discipline. Design space exploration provides the opportunity to compare multiple solutions together based on the daylighting and structural performance (Figure 9). Therefore, a design option which is good at both daylighting and structural performance can be recognized as opposed to a solution which performs well in only one discipline. In order to compare a greater number of alternatives, plotting the Pareto front graphs is more promising as it shows a better landscape of the alternatives' performance.

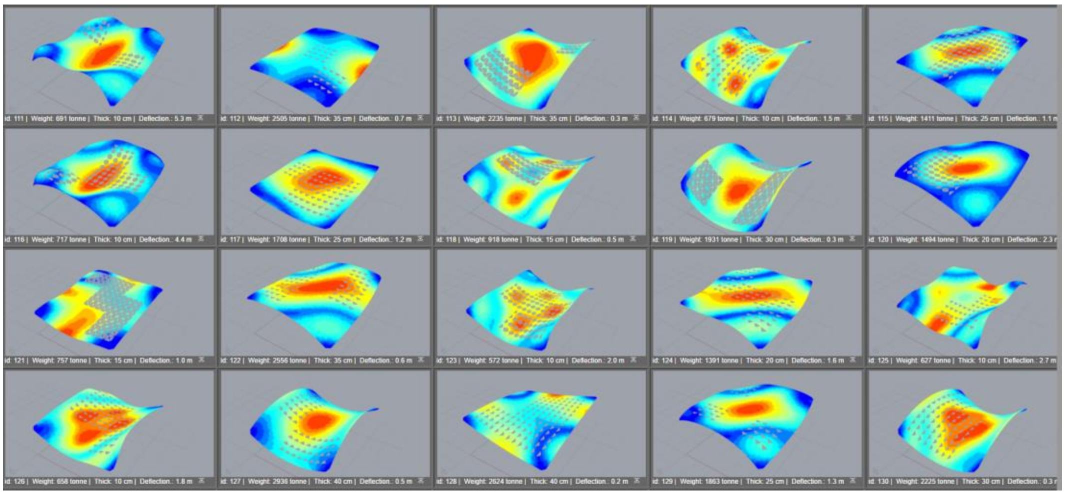
id: 111 | Weight: 691 tonne | Thick: 10 cm | Deflection.: 5.3 m
id: 112 | Weight: 2505 tonne | Thick: 35 cm | Deflection.: 0.7 m
id: 113 | Weight: 2235 tonne | Thick: 35 cm | Deflection.: 0.3 m
id: 114 | Weight: 679 tonne | Thick: 10 cm | Deflection.: 1.5 m
id: 115 | Weight: 1411 tonne | Thick: 25 cm | Deflection.: 1.1 m
id: 116 | Weight: 717 tonne | Thick: 10 cm | Deflection.: 4.4 m
id: 117 | Weight: 1708 tonne | Thick: 25 cm | Deflection.: 1.2 m
id: 118 | Weight: 918 tonne | Thick: 15 cm | Deflection.: 0.5 m
id: 119 | Weight: 1931 tonne | Thick: 30 cm | Deflection.: 0.3 m
id: 120 | Weight: 1494 tonne | Thick: 20 cm | Deflection.: 2.3
id: 121 | Weight: 757 tonne | Thick: 15 cm | Deflection.: 1.0 m
id: 122 | Weight: 2556 tonne | Thick: 35 cm | Deflection.: 0.6 m
id: 123 | Weight: 572 tonne | Thick: 10 cm | Deflection.: 2.0 m
id: 124 | Weight: 1391 tonne | Thick: 20 cm | Deflection.: 1.6 m
id: 125 | Weight: 627 tonne | Thick: 10 cm | Deflection.: 2.7 m
id: 126 | Weight: 658 tonne | Thick: 10 cm | Deflection.: 1.8 m
id: 127 | Weight: 2936 tonne | Thick: 40 cm | Deflection.: 0.5 m
id: 128 | Weight: 2624 tonne | Thick: 40 cm | Deflection.: 0.2 m
id: 129 | Weight: 1863 tonne | Thick: 25 cm | Deflection.: 1.3 m
id: 130 | Weight: 2225 tonne | Thick: 30 cm | Deflection.: 0.3

Figure 8: ParaGen's interactive website that assists the designer to explore the design space

Pareto fronts can be plotted in only one discipline: as an example, weight versus displacement is plotted to find the well-performing alternatives that have a low weight as well as meeting the serviceability criteria. Design space exploration can be further filtered, in order to focus on a specific shell typology. For example, one might want to look at the weight versus maximum displacemnet limited specifically to a dome-shaped, vault shaped or a saddle shaped shell (Figure 10). Exploration can be further narrowed, by looking at a specific thickness of a specific shell typology. As an example, one might want to compare the 10 cm thick saddle-shaped shells to the remaining saddle shaped shells (Figure 11).

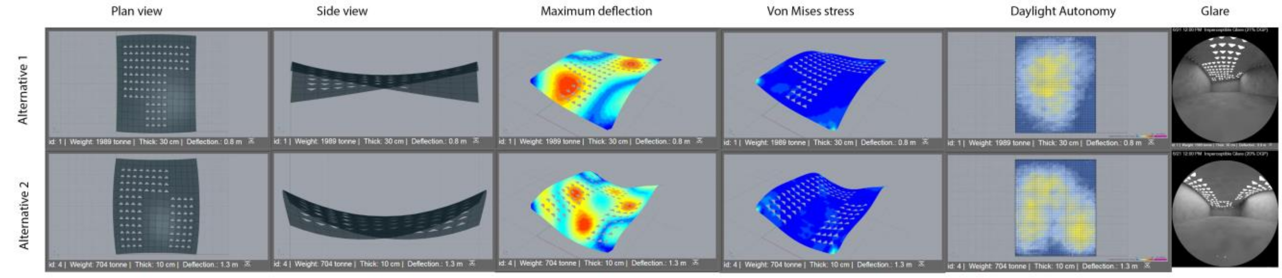

Figure 9: Coupled analysis regarding daylighting and structural performance

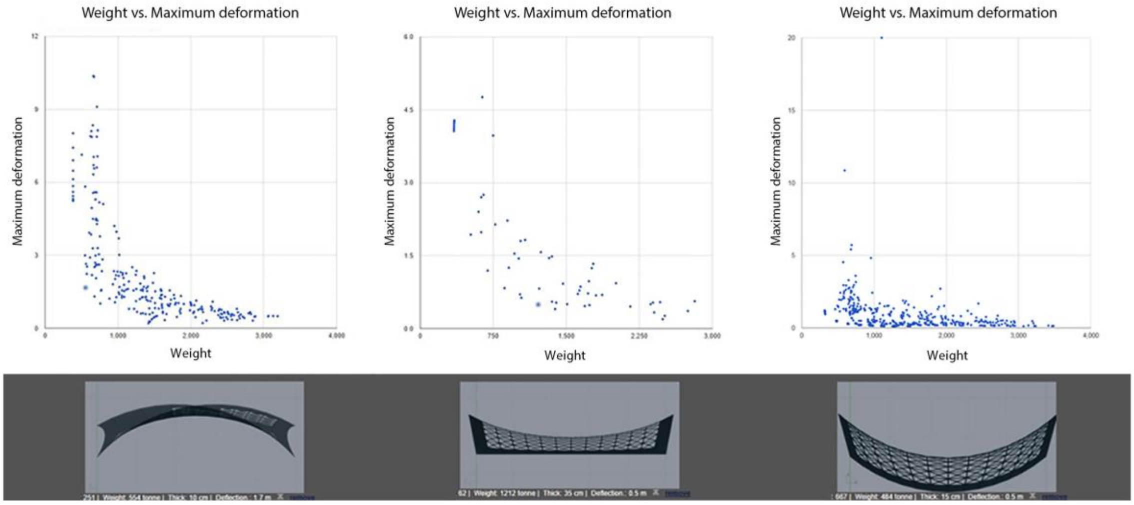

Figure 10: Interactive plots of weight versus displacement for specific shell typologies (from left to right: a dome, vault and saddle)

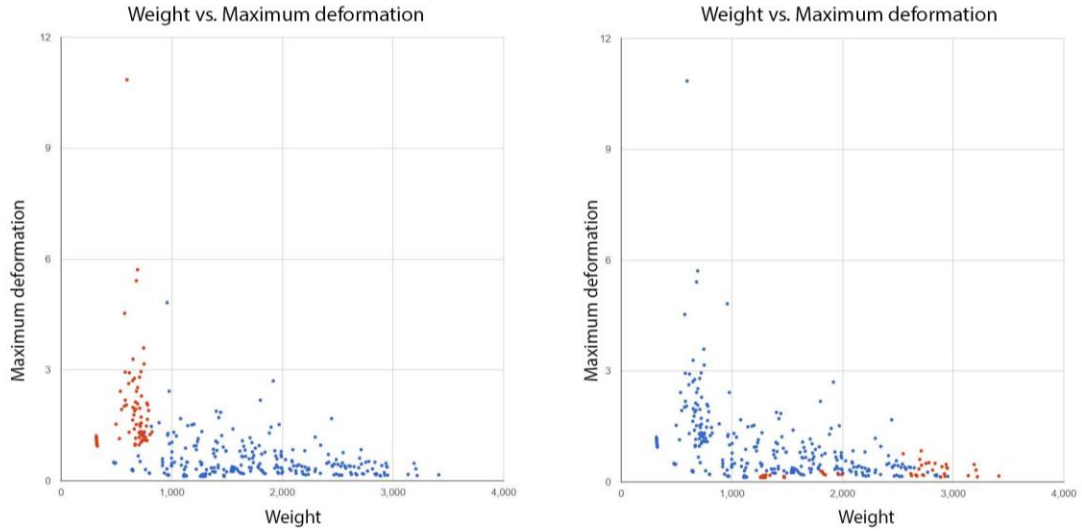

Figure 11: Exploring saddle-shaped shells based on their weight-displacemnet performance. The (left) 10 cm thick shells and (right) 40 cm thick shells are presented as red dots

Pareto fronts can also be plotted based on both structural and daylighting disicpline. Since the metrics for measuring different disciplinary performance criteria are different, a set of selected variables have been transferred to cost: material cost tied to the weight of the structure, and operational cost tied to the lighting, heating and cooling energy load when an alternative is used to cover a courtyard. This provides a common ground for conducting multi-disciplinary multi-objective analysis (Figure 12). The parallel bands of points shown in this plot represent different shell thicknesses ranging from 10 to 40 cm. It should also be noted that operational cost is calculated over one year, and if it is calculated over a 10, 20 or 30 year period, the plot scale will change.

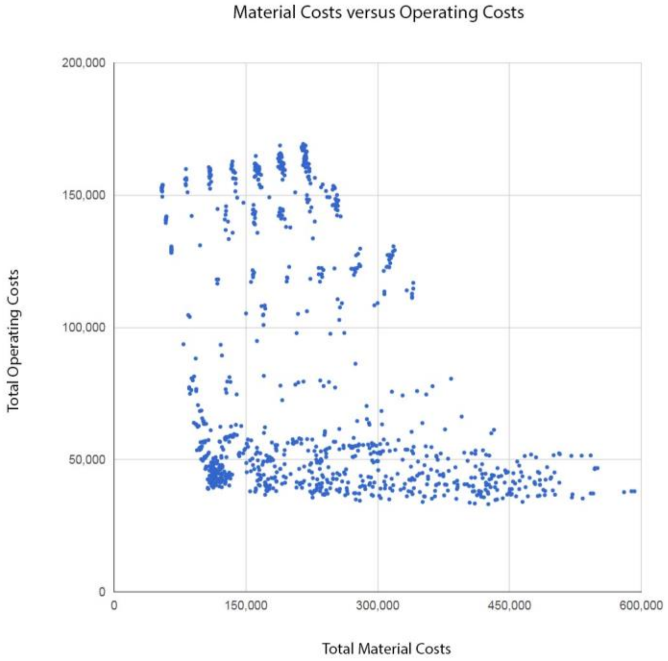

Figure 12: Material cost versus operating cost

4. Discussion

Computer scientists have been seeking ways to progress from single objective problems to multi-objective problems. Based on the work of French-Italian economist and sociologist, Vifredo Pareto, currently Pareto-optimization is the most widely used multi-objective search technique for problems with conflicting parameters (Diwekar [3]). An algorithm needs to be used to determine a representation of the Pareto optimal set. Genetic algorithms (GAs), a posteriori algorithm, is used in ParaGen in order to generate solutions from an initially randomly-generated pool of alternatives. A complete and more detailed description of ParaGen using a Non-Destructive Dynamic Population Genetic Algorithm (NDDP GA), along with a comparison between two selection methods namely “a multi objective selection using SQL queries” with “selection through a Pareto set” is presented in another paper [19]. Interactive design space exploration provides the opportunity of exploring design alternatives regarding various performance criteria. There can be multiple objectives within one discipline to be defined as the acceptable performance, or multiple objectives within multiple disciplines can be set. This is research in progress that aims to study the relation between the structural and daylighting performance of perforated shell structures spanning a range of geometries and topologies. The results will contribute to the area of computational search, multi-objective, multi-disciplinary performance assessment, as well as shell structures.

5. Conclusion

From a topological standpoint, continuous and grid shells are two ends of one continuum: as more holes are added to the surface of the shell, force flow is constantly changed and redirected, until it is channeled through the discrete members of the grid shell. In this topological transition, structural performance, including weigh, maximum deflection and maximum von Mises Stress, are in continuous transition. From another point of view, the amount and distribution of incoming daylight is in fluctuation. This paper studied the complex interwoven dynamics of form, structural and daylighting performance. The ParaGen framework is used to couple the two disciplines, by linking together any commercial or public domain simulation software to accomplish the performance analysis. In this way, both structural and daylighting performance values are available to assess the performance of each solution. Since the metrics for measuring different disciplinary performance criteria are different, a set of selected variables have been transferred to cost: material cost tied to the weight of the structure, and operational cost tied to the lighting, heating and cooling energy load when an alternative is used to cover a courtyard. This provides a common ground for conducting multi-disciplinary multi-objective analysis. This is a research in progress, and the next step is to conduct sensitivity analysis to understand the effect of design parameters on the performance criteria.

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