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Daylight as an evolutionary architectural form finder

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Abstract

This paper presents a generic tool for generation and finding of curvilinear ceiling form according to required criteria of daylight uniformity ratios. A Genetic Algorithm was utilized as a process that simulates the behaviour and adaptation of a number of competing solutions through control nodes, as generations are created, tested and selected through repetitive mating and mutation. The computer implementation was developed and coded in LUA, a versatile scripting language. Radiance simulation software was employed as the backend daylighting performance calculation engine, and Ecotect as the front end form input and visualization tool. Conclusions about the optimum ceiling geometry and form for a designed example case were drawn, leaving the architect with a variety of choices for design. Results showed that this approach offers a robust and yet precise form finding method.

Keywords: daylighting, optimization, genetic algorithms, architecture, architectural form finding

1 Introduction

Digital technologies are changing architectural practice, research and education in ways that only few were able to anticipate just a decade ago. Today, digital architecture design processes and tools allow for dynamic, open-ended and unpredictable realizations of three-dimensional structures and are giving rise to new possibilities for architectural spaces. Form is no longer something static that is imposed on a structure, nor a behaviour that can be integrated in the characteristics of 3d modelling, but is now influenced by the properties of the digital tools used. Evolution of form generation becomes based on performative strategies, as emphasis shifts from the "*generation of form*" to the "*finding of form*". This evolution can be described as generation of form while having instantaneous feedback on its performance from different perspectives, suiting various situations according to geographic locations and environmental conditions (Kolarevic, 2005).

Research based on performative optimization of architectural form parameters is well established. Significant publications in the past decade include an introduction of a new method to control building form by hierarchical geometry relationships. This process explored building form without being restricted to a simple box, using Genetic Algorithms (GA) and EnergyPlus simulation engine to optimize building form based on heat flow, heat gain, heat loss and volume (Yi and Malkawi, 2009). Another research also utilized GA's and Radiance lighting simulation program to present a technique for the design of slat-type blinds based on their relative light intensity distribution (Tsangrassoulis et al., 2006). GA controls were also used with Computational Fluid Dynamics (CFD) program Fluent, presenting geometry evolution that allows architects to experience the morphing of a design based on a set of performance targets (Malkawi et al. 2005). Moreover, GA's have been used to control energy simulation program DOE-2 to manipulate window size and placement, as a means of minimizing energy consumption (Caldas and Norford, 2002).

This paper presents a Computer Aided Architectural Design (CAAD) tool for optimizing a generic curvilinear ceiling form in accordance with daylight uniformity. A Genetic Algorithm was programmed in LUA code, allowing interactions between Radiance lighting simulation software (Ward and Shakespeare) and Ecotect conceptual building performance tool. The paper is organized as follows: First, an explanation of the generic methodology for optimizing a curvilinear ceiling form; a case is presented as an example. Results are then stated, analyzed and discussed, to be concluded with potentials, limitations and recommendations for future developments.

2 Ceiling form optimization methodology

Previous attempts to find form based on performance measures were oriented towards finding solutions that either disregarded daylighting as a passive technique to conserve energy and provide visual comfort, or didn't deal with complex curvatures as free form geometric possibilities. However, this paper presents the development of a performance based optimization algorithm that finds curvilinear ceiling form according to criteria of daylight uniformity in indoor spaces.

2.1 Daylighting / ceiling problem formulation

Lighting, in general, and daylighting design specifically, is a strategy that can be an amalgamation of the visual and the performative. Utilization of natural light in internal spaces creates large energy savings and provides a productive atmosphere for users. This sensitive aspect in environmentally aware architectural design depends on many interfacing factors. In this research, ceiling geometry is investigated as an element that can provide control to natural light, achieved through reflection and diffusion of the external reflected component of daylight. Two previous studies showed the importance of ceiling geometry in daylighting (Freewan et al, 2008; Freewan et al, 2009).

The generic ceiling form chosen is a sweeped B-spline (Figure 1), as a parametric section for an extruded surface of (m) control points. The curve equation is traced by the function:

$$\mathbf{C}(t) = \sum_{i=0}^{m} f_i(t)\mathbf{P}_i \, ; \; t \in [0,1]. \tag{1}$$

Where **P**i is the set of control points, and *fi*(t) are piecewise polynomial basis functions . A set of control points would be:

$$P_i^w = (w_i x_{i,} w_i y_{i,} w_i x z_{i,} w_i) \tag{2}$$

Where Wi is the weight pulling the curve towards control point Pi as it increases, or moving the curve away as it decreases.

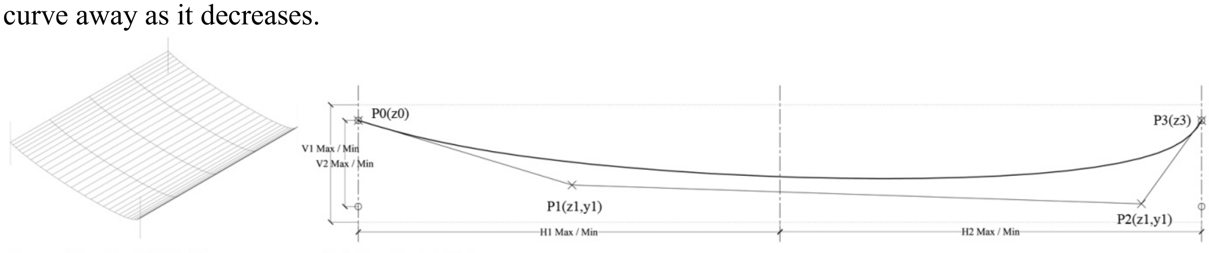

Figure 1: Example cubic B-spline ceiling with four control points (P0, P1, P2 and P3).
Where ($V1_{min} < z1, z2 < V1_{max}$), ($V2_{min} < z0, z3 < V2_{max}$), ($H1_{min} < y1 < H1_{max}$) and ($H2_{min} < y2 < H2_{max}$).

2.2 *Optimization process*

The technique used in this research for ceiling form optimization was the Genetic Algorithm (GA). It is a process that simulates the behaviour and adaptation of a number of competing solutions through control nodes, mimicking natural biological evolution through operations of population, crossover, and mutation. A GA is initiated with randomly chosen control nodes (genes), forming parent solutions of the ceiling (chromosomes) from search parameters to create an initial population. The population then evolves towards the better chromosomes by applying a fitness function that evaluates the performance of each chromosome, to be later selected according to its performance fitness as parents to generate a new population. Generations are created, tested and selected through repetitive mating and alteration. This is built on the natural principal “survival of the fittest”.

In this research, an initial population of (n) chromosomes, composed of (m) genes is randomly generated in a matrix:

$$Domain = \begin{bmatrix} Z_0^1 & Y_1^1 & Z_1^1 & Y_2^1 & Z_2^1 & . & . & . & Y_m^1 & Z_m^1 & Z_{m+1}^1 \\ Z_0^2 & Y_1^2 & Z_1^2 & Y_2^2 & Z_2^2 & . & . & . & Y_m^2 & Z_m^2 & Z_{m+1}^2 \\ . & . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . & . \\ Z_0^n & Y_1^n & Z_1^n & Y_2^n & Z_2^n & . & . & . & Y_m^n & Z_m^n & Z_{m+1}^n \end{bmatrix} \quad (3)$$

Where rows of the matrix are chromosomes and columns denote a Cartesian position value for each gene of the ceiling, as previously represented in Figure 1.

When each chromosome is generated, it is tested by a performance fitness function. The function used to evaluate ceiling chromosomes is daylight uniformity ratio, expressed as:

$$\mathbf{F}(x) = Emax / Emin \quad (4)$$

Where **F**(x) is the uniformity fitness value, Emax and Emin are the maximum and minimum illuminance values of the analysis grid.

Reproduction is then executed through random selection of parent ceiling chromosomes for breeding according to their fitness. This means that chromosomes with a higher fitness performance have a higher chance to be part of the next population. Since uniformity ratio -by nature- represents higher fitness through minimal values, an inverse of the fitness function was used to create a roulette wheel for random selection of the chromosomes that would be used to create the new population:

$$\mathbf{F'}(x) = 1 / \mathbf{F}(x) \quad (5)$$

Where F’(x) is the inverse of uniformity.

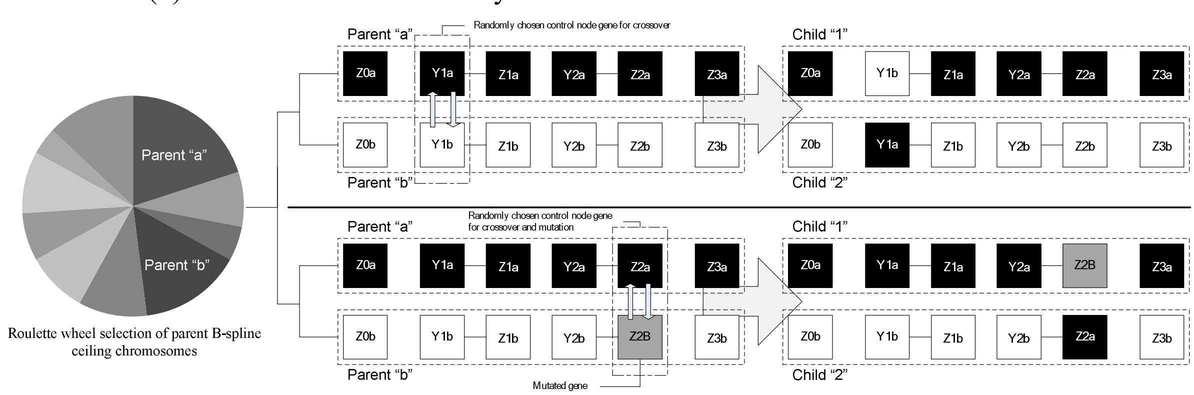

Figure 2: Process of evolution through parent selection, crossover and mutation.

Random roulette selection is then applied, and two chromosomes are chosen for either operation of cross-over or mutation (Figure 2), populating new generations to be tested and reselected as a process of evolutionary search-and-find. After the evolution of the initial population through many generations, the ceiling chromosomes within the final populations will generally be much better than the chromosomes within the initial population on average. Also, the near optimal chromosomes will be found within the generations populated.

This research utilized Radiance simulation software for analysis of daylighting performance as the backend daylighting calculation engine, and Ecotect as the front end form input and visualization tool. The computer implementation was coded in LUA, a versatile scripting language. A schematic of the combination of GA and B-spline celing form finding is presented in Figure 3.

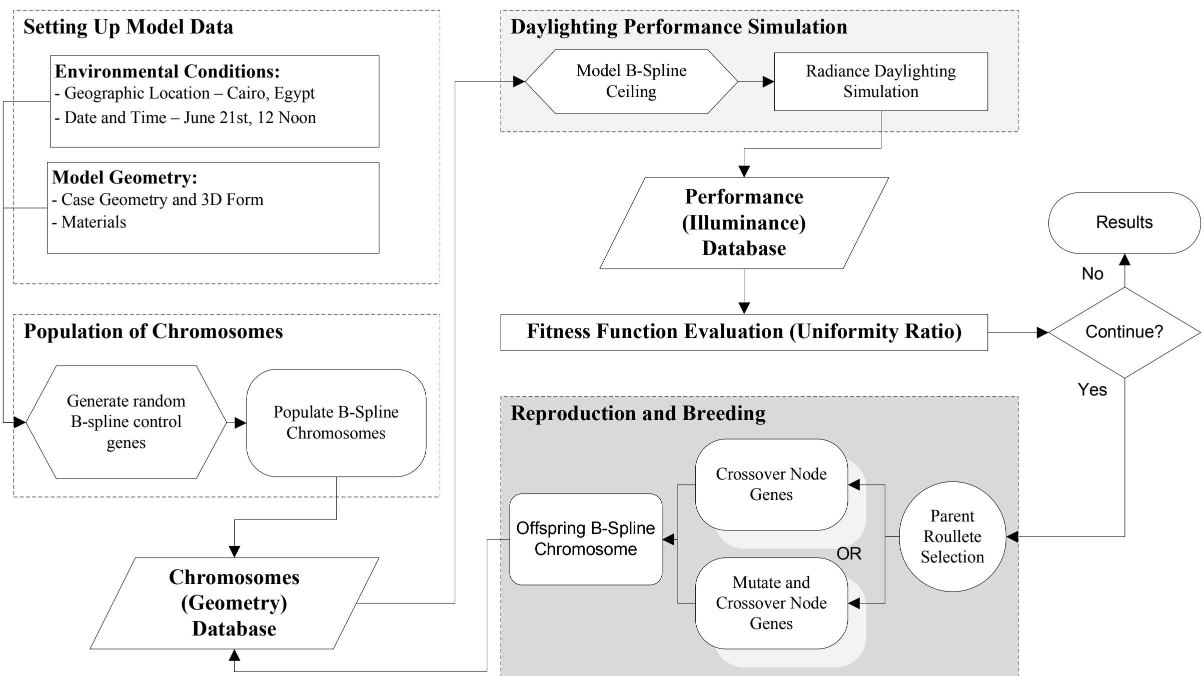

Figure 3: Schematic of GA process integrated with B-Spline ceiling form finding.

3 GA ceiling form finding example, results and discussion

A small gallery was designed (Figure 4) as a case that is responsive to the distribution and uniformity of daylighting levels, where the ceiling geometry can affect the daylighting performance to significant extents. Simulation parameters were as follows:

Location: Cairo, Egypt (Latitude: 29.8, Longitude: 31.3).
Date and time: June 21^{st} (summer), 12 Noon.
Sky condition: clear sky with sunshine.
External ground reflectance: 20% - medium colored stone.
Walls reflectance: 56% - off white color paint.
Ceiling reflectance: 85.7% - plasterboard.
Floor reflectance: 59.2% - grey colored concrete.
Glass visible light transmittance (VLT): 85%.
Analysis grid: 20 measuring point in a grid of 2.5m *2.5m at a height of 0.75m.
Four B-spline ceiling control nodes (P0, P1, P2 and P3) with limitations:

(2.0m < z1, z2 < 3.5m), (2.2m < z0, z3 < 3.3m), (0.1m < y1 < 5.4m) and (5.4m < y2 < 10.79m)

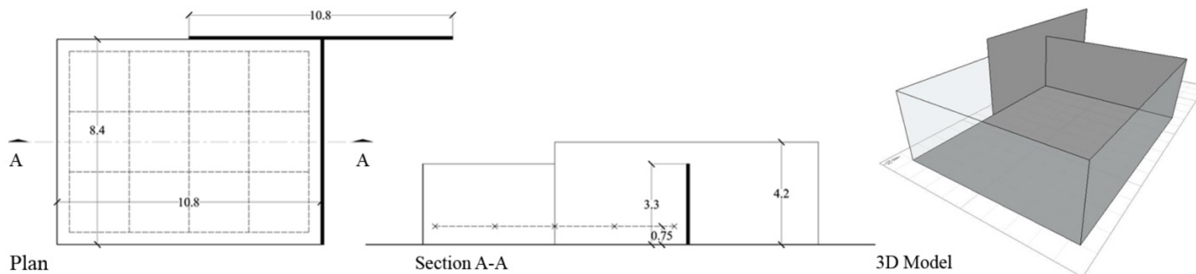

Figure 4: Assumed design parameters of the analyzed indoor space.

If an architect were to design the ceiling based on criteria of daylight uniformity at the chosen reference plane height (0.75m), what would be the optimum design geometry that provides such a requirement based on illuminance values?

The GA evolved a cubic B-spline ceiling for the case through 50 iterations, controlled by producing 50 populations / iteration (p/i) in a run and 100 p/i in another. The presented results are divided into two categories, one exploring the optimization results in analytical terms, and the other investigating the impact of geometry found on daylighting aspects.

3.1 Optimization Results

The code explored a variety of uniformity ratios in both runs (Figure 5), ranging from 5.17 to 9.66. Although the minimum uniformity ratio reached by the 50th iteration was not the lowest, the average behaviour of the chromosomes was found to be better (Figure 6). Average uniformity started with 6.75 and reached 5.59 in the 50 p/i run, while in the 100 p/i run it was initiated with 7.18 and reached 5.58. The near optimum uniformity ratio was found earlier in the 13th generation of the 50 p/i run and equals 5.19, and in the 21st generation of the 100 p/i run and equals 5.17 (Figure 6).

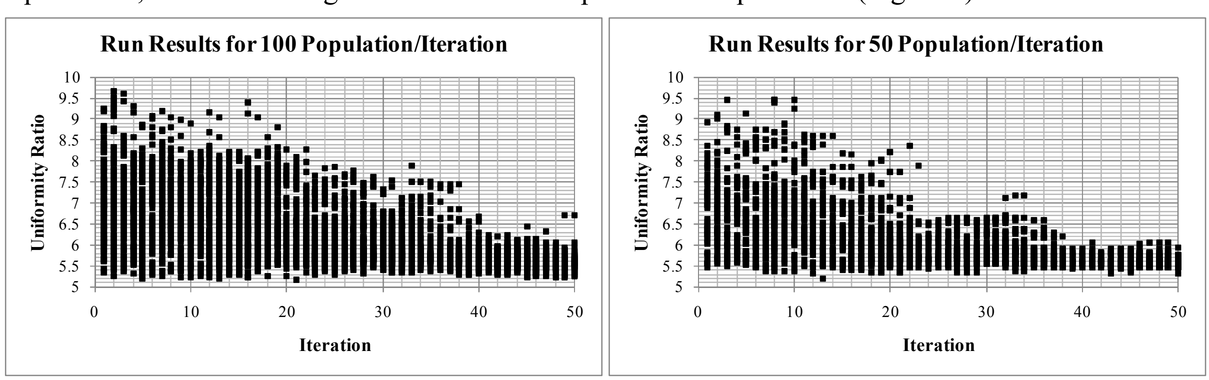

Figure 5: Iteration against uniformity ratios, GA runs results.

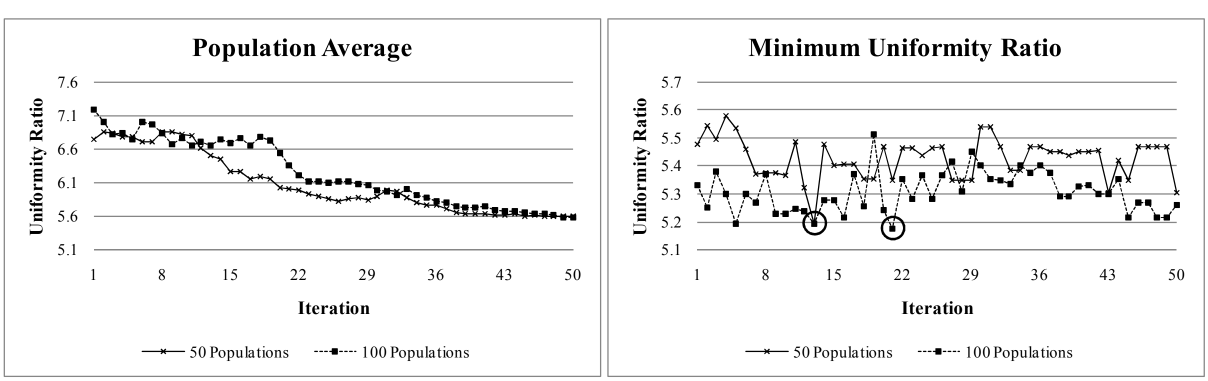

Figure 6: Iteration against uniformity ratios. Showing minimum uniformity ratios and population averages.

3.2 *Ceiling form and daylighting analysis*

The search algorithm investigated a variety of curvilinear ceiling forms (Figure 7). This diversity explained the daylighting performance expected from the explored ceiling geometry in terms of illuminance levels at reference plane and uniformity ratios. Such range of solutions provides the architect not just with options for spatial parameters, but also its expected performative behaviour.

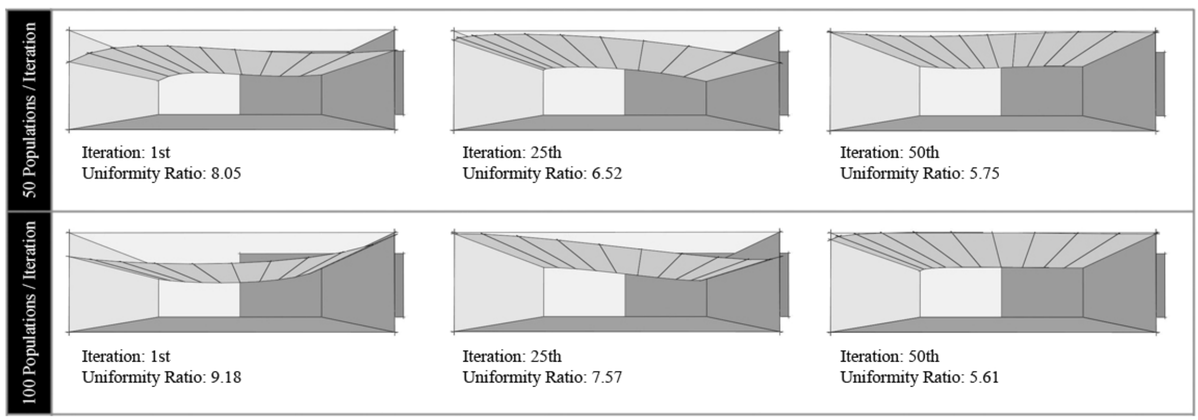

Figure 7: Selected chromosomes of ceiling form changes.

A false colour analysis of illuminance in the simulated model confirmed the contrast between the worst and best ceiling geometry found (Figure 8). In the fittest solution found, areas of lower illuminance are kept to the minimum and natural lighting levels are spread with high uniformity in comparison to the worst case.

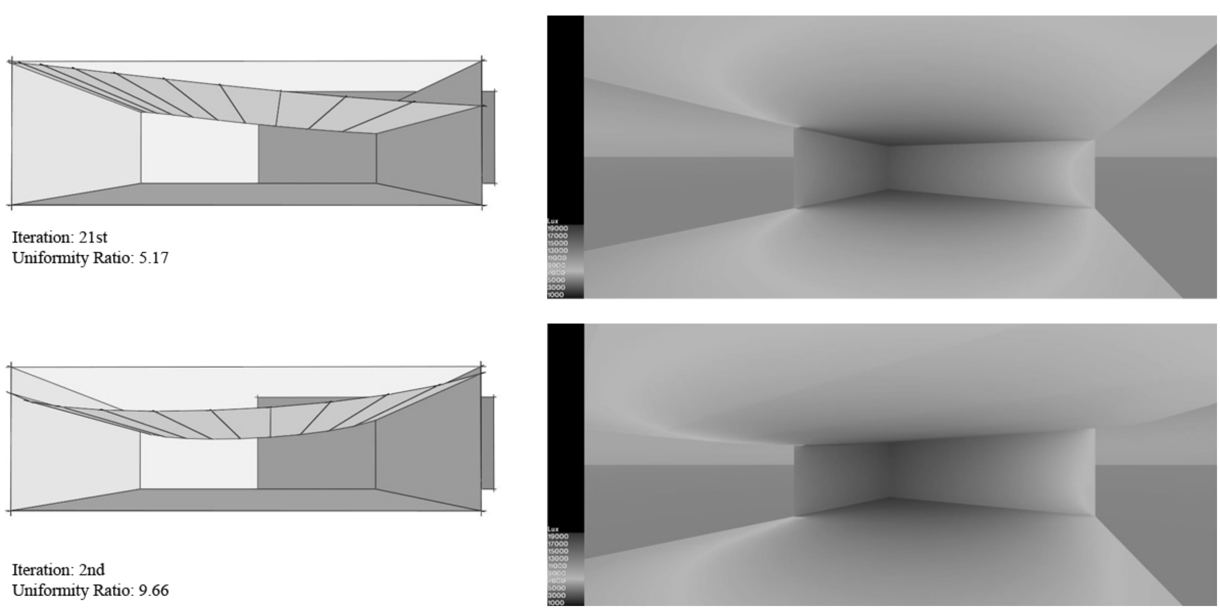

Figure 8: Best and worse solution geometry, with false colour rendering (100 p /i).

The results also revealed two possible geometrical solutions for optimum ceiling form, given the criteria of daylighting uniformity. A curvilinear ceiling solution with one half as close as possible to the ground surface at the back end of the room, providing reflections in the relatively dark corner and opening to the external reflected component at the other half. Another solution is an almost flat ceiling situated as far as possible from the ground surface, providing maximum exposure to the exterior and thus achieving uniformity through increase of overall available daylight (Figure 9).

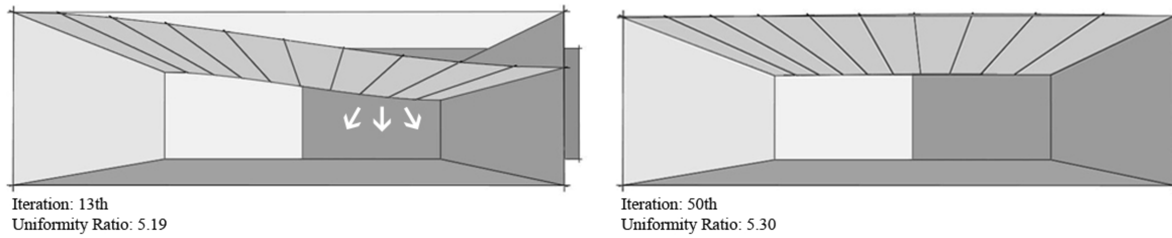

Figure 9: Ceiling geometry that gives comparable performance, allowing choice in optimum design (50 p/i).

4 Conclusion

This research presented a generic tool for finding curvilinear ceiling form algorithmically, by optimizing conceptual design based on daylight uniformity. A GA was used as a process that simulates the performance of a number of solutions through control nodes, as generations were created, tested and selected through repetitive mating and mutation. This approach offers a robust and yet precise form finding method. The acquired results from an example case showed great diversity, and then the GA converged them to a number of near optimal solutions. Through this procedure, the code demonstrated different novel directions for performativly fit geometry, which leaves the architect with a variety of choices for design. The computer now becomes more than a visualization tool; an unbiased tireless partner in design with extraordinary ways of approaching problems.

The addressed problem is presented as an example of performative optimization using GA's. However, other multi objective problems can be tackled with the same procedure, as the objective of optimization can be changed into many building performance criteria (including solar radiation, air flow, acoustics, etc…). Also, further study of ceiling geometry in regards to daylighting strategies is required, as the procedure presented dealt with a two dimensional approach through section design and extrusion. A three dimensional approach can be further developed using a surface mesh, NURBS or other forms of complex geometry to reach near optimal solutions for different orientations, seasons and time of the day.

References

CALDAS, L. and NORFORD, L., 2002. A design optimization tool based on a genetic algorithm. *Automation in Construction*, 11, 173-183.

FREEWAN, A.A. SHAWO, L. and RIFFAT, S., 2008. Optimizing performance of the lightshelf by modifying ceiling geometry in highly luminous climates. *Solar Energy*, 82, 343-353.

FREEWAN, A.A. SHAWO, L. and RIFFAT, S., 2009. Interactions between louvers and ceiling geometry for maximum daylighting performance. *Renewable Energy*, 34, 223-232.

KOLAREVIC, B., 2005. Computing the performative. In: KOLAREVIC, B. and MALKAWI, A., eds. *Performative Architecture: Beyond Instrumentality*. New York: Spon Press.

MALKAWI A., SRINIVASAN, R., YI, Y. and CHOUDHARY, R., 2005. Decision support and design evolution: integrating genetic algorithms, CFD and visualization. *Automation in Construction*, 14, 33-44.

TSANGRASSOULIS, A., BOURDAKIS, V.,GEROS, V. and SANTAMOURIS, M., 2006. A genetic algorithm solution to the design of slat-type shading system. *Renewable Energy*, 31, 2321-2328.

WARD, G. and SHAKESPEARE, R., 1998. *Rendering with radiance. The art and science of lighting visualization*. San Francisco, CA: Morgan Kaufmann.

YI, Y. and MALKAWI A., 2009. Optimizing building form for energy performance based on hierarchical geometry relation. *Automation in Construction*, 18, 825-833.