Evolving Optimal Sun-Shading Building Façades

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EXTENDED ABSTRACT

Evolutionary algorithms have been applied to numerous architectural design applications in what is popularly known as *evolutionary design* [3], [4], [6]. Such applications include architectural support [7] and structural design for buildings [5] and floor-plan layout design [8]. However, evolutionary design of optimally shaped building façades is less explored in evolutionary architectural design applications [6], [12], [13].

This research investigates the evolutionary design of building façades, optimally shaped for a given climate. This study applies evolutionary methods to optimally design sun-shades (covering windows on building façades). Ideally, sun-shades will maximally block direct sunlight but minimize window coverage, thus allowing unobstructed views out of the window and maximizing ambient natural lighting inside. Also, sun-shades help to *passively control* building *climate* and determine occupant comfort. Optimal sun-shade designs allow direct sunlight (*solar penetration*) to enter interior spaces in winter months, heating the building, and minimize solar penetration in summer months, cooling the building [11].

This study applies an *Evolutionary Strategy* (ES) [1] to automate sun-shade design such that solar penetration is minimized for both east and west facing windows, given summer solstice daylight hours in various geographic locations. An ES was selected given the demonstrated effectiveness of such evolutionary optimization on a range of engineering design problems with various constraints [9]. We focus on sun-shade design for rectangular shaped windows (vertical Y *axis* is 1.5 times the length of the horizontal X *axis*), where we anticipate sun-shade design will be replicated for many identical windows comprising a building's façade, as is the case for many modern tall buildings [14].

The ES was initialized with 20000 *uniform random* [1] points in a continuous three-dimensional (1.0 x 1.0 x 1.0) space adjacent to the window (figure 1). These points were possible mesh vertices for sun-shade design and thus the design solution space. The fitness function computed sun-shade effectiveness via calculating how many sun-rays were blocked assuming an increasing or decreasing sun height above the horizontal plane (angle V in figure 1). Thus, we tested the portion of sun-rays blocked by an evolving sun-shade (mesh formed by 20000 vertices) over half of daylight hours (separate sun-shades were evolved for east and west facing façades). In successive generations, sun-shade mesh vertices blocking sun-rays (at varying degrees of inclination and declination) aimed at the window were selected for as vertices in evolving designs.

Evolving sun-shade effectiveness was computed as the intersection of sun-rays at 15 second intervals during simulated half-days. For east facing façades, from the point where sun is on the horizontal plane (Y *axis* in figure 1) and incrementally increases until it is directly above the vertical axis of the building façade (*Y-Z plane* in figure 1), and for west facing façades where the sun starts at this midday point and incrementally declines. Sun-shades were evolved for east and west facing façades given *half* of summer solstice daylight hours[1] (for east versus west façades) indicative of *Cape Town*, South Africa, and *Amsterdam*, the Netherlands (~ 14 hours, 25 minutes and 16 hours, 48 minutes, respectively).

At these two geographic locations, 15 second intervals indicated incremental sun movements during day-light hours. For Cape Town, this was approximated as 0.052° increases and decreases and for Amsterdam, 0.045° increases and decreases (for east and west facing façades, respectively). Half-day simulations thus tested, every 15 seconds, sun-ray intersection (vector: X_p, Y_p, Z_p at angle V from the horizontal or vertical plane) with any point in the sun-shade. This was a point-cloud in generation 1 and mesh-points in subsequent generations (figure 1). Points intersecting the sun-ray were given maximum (normalized) fitness of 1.0, and points within a given *ray distance* were assigned a logarithmically decreasing fitness that equalled 0.0 at the maximum *ray distance*. To account for random variation and diffusion of sun-ray light, each 15 seconds, a random angle (in the range: $[-0.01°, +0.01°]$) was added to the sun-ray's vector value V.

Evolutionary design used a μ+λ ES [1], where (λ = 20000) offspring were created per generation. This combined population was ranked by fitness and the least fit λ genotypes discarded. Each genotype encoded an (x, y, z) point in an N point-mesh (evolving sun-shade design), and corresponding σ mutation step-size for each coordinate. For simplicity, the X, Y, Z dimensions of the 3D *solution*

[1]https://www.timeanddate.com/sun/

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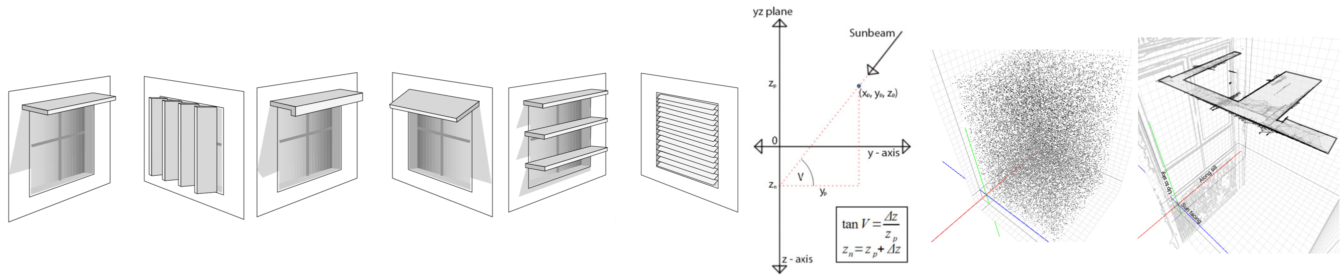

Figure 1: Left: Example typical sun-shades [10] tested for effectiveness comparisons with fittest 10 evolved sun-shades. 3rd-right: Computing sun-ray vector intersection with sun-shades [11]. 2nd-right: Initial 20000 points for evolutionary sun-shade design. Far-right: Example fittest evolved sun-shade for east facing façades in *Cape Town* (experiment set 1).

space for evolving sun-shades (adjacent to the window) was normalized the range [0.0, 1.0] and the window dimensions normalized to the range [0.0, 1.5] for the X, Y window axes, respectively. Thus, sun-shades only evolved to cover the top two-thirds of a window, ensuring that sufficient ambient light still entered the building and that occupants have a view out of the window.

One generation was the evaluation of all 20000 genotypes (in sun-ray simulations), where the fittest 10% were selected, mutation operators: $\sigma_x N_x(0,1)$, $\sigma_y N_y(0,1)$, $\sigma_z N_z(0,1)$ applied to permutate each genotype's coordinate and step-size values (p=1.0 and p=0.05, respectively), such that (λ=20000) offspring genotypes were created. All μ+λ genotypes were then evaluated and the fittest 20000 selected as survivors [1]. Sun-shade evolution for Cape Town and Amsterdam constituted experiment set 1 and 2, respectively. Each experiment set was 10 ES runs, for east and west facing façades, and each run was 100 generations (ES run stopping condition).

Sun-shade fitness was the portion of points (constituting a sun-shade design) that blocked or partially blocked sun-rays during each half-day simulation. Points that intersected a sun-ray were assigned a maximum fitness of 1.0, and points close to a sun-ray (< *ray distance*) were assigned a partial fitness in the range: (0.0, 1.0). In generation 1, all 20,000 possible points were considered for sun-shade design. In subsequent generations only points given a fitness value were considered part of the evolving sun-shade (point-mesh) design. For simplicity, sun-shade fitness was normalized to the range: [0.0, 1.0], where 0.0 indicated no sun-rays blocked and 1 indicated all sun-rays blocked (over all day-light hours tested).

As a benchmark comparison for evolved sun-shade effectiveness, the fittest sun-shades evolved for east and west facing façades (at both locations) were selected from each run and compared to ten *heuristic* design sun-shades (figure 1). The effectiveness of these sun-shades was similarly computed using sun-ray simulations of 15 second intervals during half-day periods for east and west facing façades and a given number of day-light hours at both locations.

Thus for each heuristic design sun-shade a *fitness* value was similarly calculated, normalized to the range: [0.0, 1.0], where 0 indicated no sun-rays were blocked and 1.0 indicated that all sun-rays were blocked during a sun-ray simulation.

Results indicated that, on average, evolved sun-shades, for both shorter and longer day lengths and east versus west facing façades, were significantly more effective (with statistical significance, two-tailed t-test, $p < 0.05$, [2]) compared to the ten tested heuristic designed sun-shades. Results also indicated that evolutionary design is suitable for automating optimal sun-shade (and potentially building façade) design and support current hypotheses on the efficacy of evolutionary design for improving current architectural designs and automating efficient and effective industrial design production [3], [4], [12]. Ongoing work is evaluating sun-shade evolution in comparison to other heuristic designs in various geographic locations, as well as evolving sun-shades that dynamically adapt their form to suit varying daylight lengths and sun intensity.

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