SHADING DESIGN FOR OUTDOOR LEARNING IN WARM AND HOT CLIMATES USING EVOLUTIONARY COMPUTATION: A CASE STUDY IN HOUSTON TX.

Mili Kyropoulou

Gerald D. Hines College of Architecture and Design,
University of Houston
4200 Elgin St, Houston, TX 77204, USA
mkyropoulou@uh.edu

ABSTRACT

This research proposes a parametric workflow to environmentally optimize the shading design of outdoor educational spaces using multiobjective evolutionary algorithms. The design variants that are parametrically evaluated against thermal and visual comfort indices and the economy of the structure are shading growth and permeability. Part of the investigation is optimizing geometric modeling, environmental parameter benchmarking, evolutionary solver parameters definition, solution analysis, and the solution selection process. Outdoor thermal comfort is assessed using the Universal Thermal Climate Index, and visual comfort using horizontal illuminance levels and daylight uniformity. Minimizing the required shading area is used as a material resource consideration. The results showed that the solver could reach stability early on; therefore, a smaller population could lead to similar results and that material consideration is fundamental to the optimization process. The validation of the selected solution proved the effectiveness of the shading and the ability of the methodology to assist early design.

Keywords: outdoor comfort, thermal and visual comfort, outdoor educational spaces, evolutionary parametric optimization, shading design

1 INTRODUCTION

Following the outbreak of the COVID-19 pandemic and the reports of lower risks of infection in the outdoors (Belosi et al. 2021), people have been encouraged to spend more time outdoors as a safety mechanism to cope with the crisis. Spending time outdoors is one of the easiest ways to improve mental, physical, and emotional health and well-being (Echouffo-Tcheugui et al. 2018; Razani et al. 2019; Meredith et al. 2020). Recent studies (Morse et al. 2020; Grima et al. 2020) indicate the increased demand and value attributed to natural areas in times of crisis. A more specific focus on educational spaces reveals positive effects of outdoor learning on students' physical activity levels (Mygind 2007), mental health (Gustafsson et al. 2012), social competencies (Hartmeyer and Mygind 2016), academic achievements (Fägerstam and Samuelsson 2014), and students engagement in classrooms (Kuo, Browning, and Penner 2018).

Several studies have provided extensive information on the effects of outdoor climatic conditions on people's thermal sensation, including an overview of the metrics and benchmarks used (Nikolopoulou 2011; Lai et al. 2020). Shading plays a fundamental role in outdoor spaces since it can help block direct solar radiation and affect outdoor thermal comfort. Many outdoor comfort studies highlight the importance of shading in warm and hot climates by examining people's preferences and observing their role in outdoor thermal comfort (Spagnolo and de Dear 2003; Nikolopoulou and Lykoudis 2006; Lin 2009; Ng and Cheng 2012; Yang, Wong, and Jusuf 2013). A study on occupancy patterns and pedestrian routes in a university campus outdoor spaces used spatial statistical analyses to show that the adequacy of shading elements plays an essential role in expanding the use of outdoor areas on campus during the hot season (Göçer et al. 2019).

Anthropogenic global warming significantly affects the duration of warm and hot seasons in all climates, including the coldest ones. Incorporating a robust performance-based design approach for outdoor shading is becoming more prominent irrespective of the climate.

This paper presents a computational workflow to design a performance-based shading device for an outdoor educational space suitable for warm and hot climates, using a generative and scalable approach. Central to the investigation are the selection of the input parameters – evaluation period, climate change, sky heat exchange, and surface temperatures - and the definition of the environmental benchmarks. The study begins with an overview of thermal and visual metrics to identify the most suitable for evaluating outdoor educational spaces. It continues with an overview of related studies and discusses their methods and effectiveness, how they influenced the methods used, the objectives selection, and the benchmarking. Finally, the paper presents an optimization process through a case study and concludes with the analysis and verification of the results, searching for an optimal solution as an early design guideline.

2 RESEARCH CONTEXT

2.1 Existing Workflows and Study Contribution

Environmental Simulation Tools (ESTs) are used extensively for indoor environments and occasionally outdoors only to demonstrate their effect on buildings performance. During the past decade, there have been significant advances in calculating outdoor thermal comfort metrics using computational tools, accompanied by significant yet limited attempts to utilize ESTs to inform the design of outdoor spaces. Visual standards for the outdoors are still limited to artificial lighting.

One of the first attempts to simulate outdoor thermal comfort more comprehensively was incorporating the sky view component to calculate a corresponding solar-adjusted temperature for a static shading design (Mackey, Roudsari, and Samaras 2015). A complementary workflow suggested the utilization of energy modeling to calculate annual hourly outdoor surface temperatures that, in combination with the sky view component on a grid, informed thermal comfort microclimatic mapping (Mackey et al. 2017). The same study suggested that the sky heat exchange model was the most critical parameter to emphasize in creating urban microclimate maps. More studies have found that the influence of radiation is more important than that of wind, especially during summer months or in warm and hot climates (Hwang and Lin 2007; Liu, Zhang, and Deng 2016; Tseliou et al. 2016; Shih et al. 2017). A combination of parametric tools and ESTs was used for shading designs during a workshop in Denmark (Naboni 2014), suggesting a variety of metrics to evaluate performance. Exposure to solar radiation and protection from strong winds were the most critical parameters to design for the outdoors, depending on the climate. This early experimentation with ESTs presents a reactive approach to climatic conditions and comfort and not a generative one. Daylight was used as an indication in indoor spaces and as a guideline for outdoor shelters, without specific targets on what constitutes outdoor visual comfort. One study used evolutionary computing to optimize the shape and movements of kinetic elements. Rodonò et al. (2020) presented a parametric workflow that added the effect of wind patterns in calculating outdoor comfort using three point-in-time calculations beneficial to prove the effectiveness of a movable structure. Most recently, a design study of dynamic structures utilized multiobjective evolutionary algorithms (Chi et al. 2021) using nine point-in-time simulations to optimize form relative to changing solar geometry during the year and its effect on thermal comfort.

The paper expands on multiobjective evolutionary computing by utilizing annual and seasonal simulations instead of point-in-time ones. In addition, it suggests a way to include outdoor visual comfort in pair with thermal comfort during the multiobjective evaluation as a more suitable approach to assessing educational spaces. Another critical input for the simulations is the climate conditions. Climate files that account for climate change exhibit higher temperatures, extended cooling periods, and longer times with a higher heat index. Shading addresses overheating conditions; therefore, this study uses climate change projected weather files instead of standard historical ones.

2.2 Thermal Indices for the Outdoors

The physiology of thermal comfort outdoors can be described similarly to the indoor with a critical additional climatic variable, solar radiation. Several thermal comfort indices have been developed to evaluate the thermal load people are exposed to, such as COMFA (Brown and Gillespie 1986), The Outdoor Standard Effective Temperature OUT_SET (de Dear and J 2000), the Physiological Equivalent Temperature (PET) (Höppe 1999), and the Predicted Mean Vote (PMV). One significant limitation of most thermal indices is that they are based on steady-state energy balance models of the human body. People outdoors rarely experience thermal balance. In response to that, the Universal Thermal Comfort Index (UTCI) was released in 2009 (de Dear et al. 2008). UTCI uses a human energy balance model to give an equivalent temperature indicative of the heat or cold stress felt by a human body outdoors for a given combination of wind, radiation, humidity, and air temperature. The scale comprises ten categories, suggesting a no thermal stress condition from 9ºC to 26ºC. A comparative analysis between PET and UTCI revealed that UTCI accounts better for very high vapor pressure values. Therefore UTCI is considered better for warm and humid environments (Matzarakis, Muthers, and Rutz 2014; Zhang et al. 2020).

2.3 Visual Indices for the Outdoors

Although daylight assessment metrics and evaluation methodologies have been extensively studied indoors, the design of outdoor daylighting has been overlooked and understudied (Pan and Du 2021). In several countries, design standards of urban daylighting aim to assist indoor conditions or evaluate nighttime conditions with a focus on artificial lighting. There is a significant lack of information on the impact daylighting may have on the outdoors relative to outdoor activities during the day. This study uses the limited existing literature to create practical evaluation benchmarking for assessing daylight outdoors. Horizontal Illuminance Levels (HIL) measured in lux are a widely used lighting parameter in indoor and outdoor daylighting design. A study that analyzed daylight patterns and visitation trends of urban outdoor spaces in Shenzhen suggested that the most visited sites among those evaluated exhibited an average HIL of less than 30,000lux (Pan and Du 2021). This value was consistently met as a threshold that distinguished the areas with excessive glare. The present study uses HIL of 30,000lux as the acceptable upper threshold.

Another daylight quality indicator is the distribution of light called uniformity of illuminance. Uniformity of illuminance refers to the illuminance conditions on the task and the immediate surroundings. It is expressed as the ratio of minimum illuminance to average illuminance on a surface. A higher value denotes more uniformity and better visual comfort (Alrubaih et al. 2013). However, there are no guidelines for illuminance uniformity, and outdoor applications are again overlooked. In this study, it is considered more suitable to use the median value -instead of the suggested average value- as the denominator for evaluating uniformity outdoors, so extreme outlier values at the edges of the analysis surface do not skew the result.

3 CASE STUDY CONTEXT

The case study uses Houston, Texas, USA (ASHRAE Climate Zone 2A – Hot-Humid Mild Winters). as a testbed. Per the Köppen-Geiger climate classification, Houston (29.76°N, 95.36°W) is Cfa, a humid subtropical climate with tropical influences. The average daily high-temperature peaks at 94°F (34.5ºC) at the end of July, with 99 days per year above 32ºC (90°F). Relative humidity averages over 90% in the morning summers and around 60% in the afternoon resulting in a heat index higher than the actual temperature. Winds are often light in summer and offer little relief. Global illuminance is abundant all year round, and protection from excessive daylight appears to be a significant consideration. The outdoor area selected for demonstrating the analytical workflow is an open green site on the northwest side of the College of Architecture and Design building at the University of Houston. The site is partially shaded by the 4-story main building, while the western solar angles are partially obstructed by the Blaffer Art Museum building and some trees. The space is rarely used as it lacks solar protection and seating.

The space is modeled in Rhino, and design parameters are parametrized in Grasshopper, the algorithmic modeling software embedded in Rhino. The desired shaded area is a 5m (~ 3") square. An extended area above the shaded area can potentially accommodate shading at a maximum height of 3.5m (~1'), covering a maximum area of 100m^2 (1076ft^2) (Figure 1 left). The shading area is subdivided into 37cm (~ 1") square tiles. The algorithm uses attraction points (Figure 1 right), and a coverage percent defines its growth in different directions within the limits of the defined shading area. Each attraction point can move along the z-axis from 0 to 2.4m (~6.'), passing through three equally distanced levels and attracting all the remaining tiles uniformly. This function gives permeability to the structure and provides vertical shading at the perimeter. The perimeter attraction points are interpolated, lofted, and panelized per the initial subdivision, and the original tiles are projected over the newly created center points.

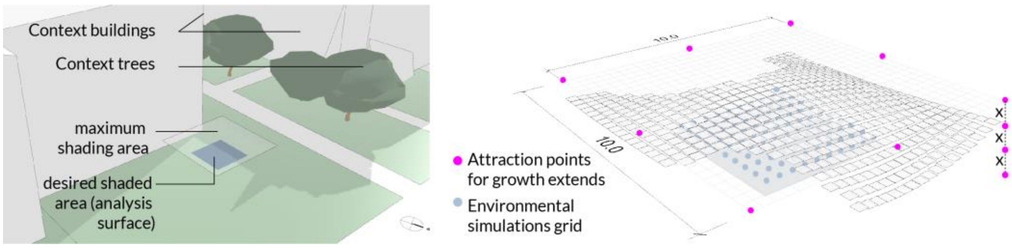

Figure 1: Geometrical input parameters in Grasshopper visualized in the Rhino scene

4 PARAMETRIC MODELING AND OUTDOOR SHADING DESIGN

The environmental evaluation uses WallaceiX version 2.65 (Mohammed Makki 2019) as an evolutionary engine that allows users to run evolutionary simulations in Grasshopper. Wallacei was chosen because it offers various options while setting up the design problem, analyzing the outputted results, and selecting solutions. WallaceiX employs the NSGA-2 algorithm (Deb et al. 2002) as the primary evolutionary algorithm and emphasizes non-dominated solutions using an elitist principle while preserving diversity, i.e., the elites of a population are carried to the next generation. The solver component requires two sets of inputs, the variables (Genes) and the fitness objectives (FO). Given the long time annual daylight simulations and comfort calculations need per iteration, a principal challenge was to minimize the number of genes and thus the time required to run a sufficient number of iterations while maintaining a valid yet time-cautious methodology to assess the design.

4.1 Shading Design Variables (Genes)

After carefully considering each input, the simulation parameters were sensibly grouped and optimized based on their relative effect on the objectives to 10 genes (sliders) and 46 total slider values, resulting in a 6.9e5 research space. Eight sliders contained in a gene pool comprise three values each that define the eight attraction points' height, resulting in 24 slider values. One slider provides 15 values of possible attraction points' combinations defining growth direction(s). The last slider provides 7 values ranging from 0 to 0.6, defining the reduction of the shading area as a percentage of the entire structure.

4.2 Environmental Criteria (Objectives) and Benchmarks

All environmental variables are computed using the simulation engines and components Ladybug and Honeybee Legacy plugins offer. Ladybug imports standard EPW files into Grasshopper and provides a variety of 3D graphics to support the decision-making during the initial design stages. Honeybee connects Grasshopper to four validated simulation engines - EnergyPlus, Radiance, Daysim, and OpenStudio - which evaluate building energy consumption, comfort, and daylighting (Sadeghipour Roudsari and Pak 2013). The climate file used is the TMY file at the Bush International Airport adjusted using Weathershift™ (Belcher, Hacker, and Powell 2005) with RCP 8.5 and a warming percentile of 50% for the median year of 2080. The fitness objectives (FO) are: (FO1): Minimize the average degree from comfort UTCI range on the analysis surface. The comfort range used is 9ºC (48.2ºF) – 26ºC (78.8ºF); (FO2): Maximize the time when average HILs remain within 300-30,000lux on the analysis surface. Although low-range illuminance numbers are not expected in this context, the lower threshold provides a safety mechanism and assures a universal application to different sky conditions; (FO3): Maximize daylight uniformity, expressed as the ratio of minimum illuminance to the median illuminance on a surface. It is expected that uniformity in illuminance levels will result in visual and thermal comfort uniformity across the analysis surface. If the average illuminance is outside the 300-30,000lux range for over 50% of the years, the script returns a 0 value. In this way, the excessively bright or dark results are not evaluated even if uniformity is achieved; and (FO4) Minimize the area of the shading surface. This criterion differentiates iterations that perform similarly based on economic and material resource considerations, ranking higher those that result in less material use.

Annual daylight simulations are performed on a 0.5m (~2") square grid on the analysis surface resulting in 100 test points. For the annual daylight simulation, Honeybee uses Radiance (Ward 1994), and the annual illuminance simulations are based on the Daylight Coefficient method using Daysim (Tregenza and Waters 1983). HIL values within the defined range and daylight uniformity are computed using Honeybee and standard Grasshopper components.

Thermal comfort mapping is performed on a 1m (~') square grid on the analysis surface placed 90cm (~3") above the shaded area, the approximate chest height of a seated person, resulting in 25 test points. UTCI calculations are performed from 8 am to 6 pm from April to October, the heat stress period in Houston for 2090. Air temperature, relative humidity, and wind velocity derive directly from the climate file. Outdoor surface temperatures derive from an annual energy simulation using EnergyPlus that runs once. The ground surfaces are virtual EnergyPlus thermal zones that approximate the finish materials, such as concrete, grass, and brick. The thermal zones of the simulation and the geometrical iterations are used as inputs to the View Factor Calculator component that generates view factors for the Outdoor Comfort Analysis Recipe to perform a Microclimate Map Analysis, as described in (Mackey, Roudsari, and Samaras 2015). The shading material is assumed to equal the thermal properties of a solid textile. It does not allow for partial or complete sunlight penetration and does not have thermal storage or thermal insulation capacity (Rodono et al. 2020). The relationship of the various inputs and outputs can be seen in Figure 2.

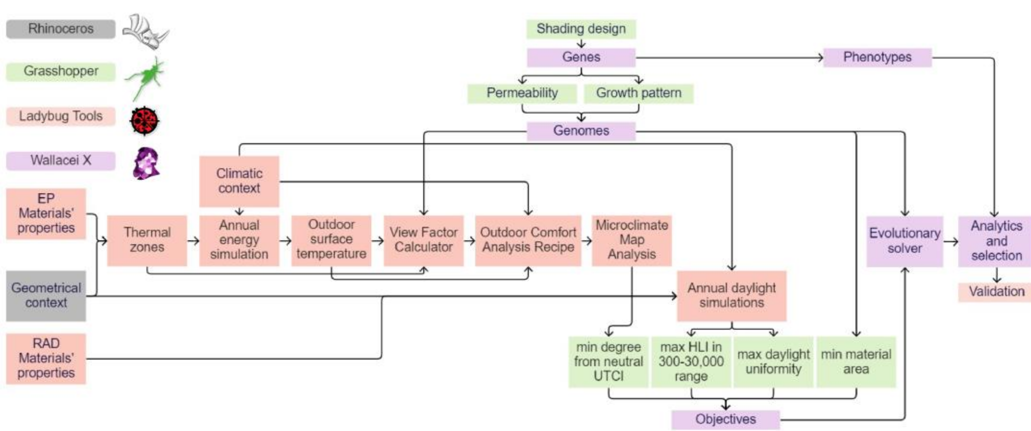

Figure 2: Workflow for the shading optimization.

4.3 Evolutionary Solver Parameters and Optimization

Inputs of the evolutionary solver follow published descriptions and recommendations (Mohammed Makki 2019). Crossover probability was set at 0.9, mutation probability at 1/n - where n is the number of variables in the design problem (Deb et al. 2002), mutation distribution index at 10, and crossover distribution index at 20. Given the size range of the evaluated shading geometries, the simulation time per iteration varied substantially, averaged at 4mins in a conventional Intel® Core™ i7-10875H CPU @ 2.30GHz Processor. Three optimization runs of the solver assisted in optimizing the process by looking at the following graphs:

Standard Deviation (SD) Graph: *The SD curves are plotted for each generation separately from the first (red) to the last (blue). They represent the distribution of the values from the mean. A low SD factor indicates less variation within the population., while a high SD factor indicates more variation.*

Mean Trendline Chart: *The mean trendline chart presents the mean fitness value for each fitness objective independently for each generation across the entire simulation from start to finish.*

Fitness Values (FV) Chart: *The FV chart analyses the FVs for each FO independently across the entire population. The aim is to visualize how the solutions are performing in relation to one another.*

Two runs optimized the population size by looking at simulation time, SD trend, and FVs. In Run 1 (R1), with a population size of 1000, generation size of 20, and generation count of 50, the simulation runtime was 40h34mins. In Run 2 (R2), with a population size of 200, generation size of 10, and generation count of 20, the runtime was 9h23mins. The Parallel Coordinate Plot (PCP) analyzes all the solutions in the population, comparing the fitness values for each solution for all FOs from the first (red) to the last (blue). The PCPs for both runs are shown in Figure 3. A similar trend for FO1, FO2, and FO3 is observed where stability is reached after the sixth generation. FO4 presents no trend across the generations and fluctuates from beginning to end. The absolute difference of the best fit values for FO1 (UTCI), FO2 (HLI), and FO3 (uniformity) is 0.49, 0.54, and 0.05, respectively, less than 0.6 of the measuring unit.

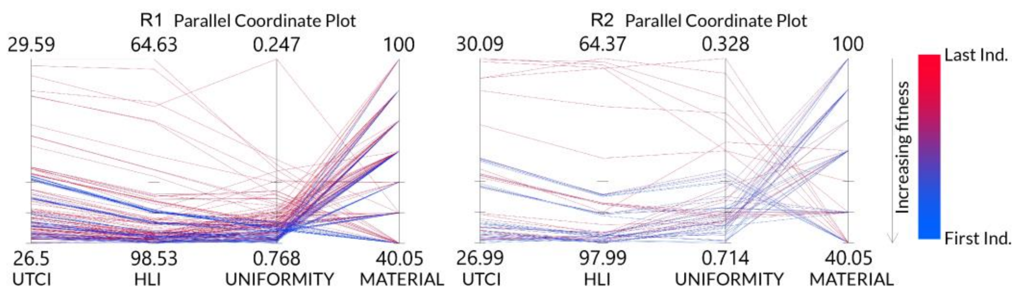

Figure 3: Parallel Coordinate Plots for Run 1 (R1) and Run 2 (R2).

The second test optimized the FOs and prioritized their importance. To better understand the contribution of accounting for the material area, Run 3 (R3) is the same as R2 without FO4. FVs were observed, and the material areas were recorded (Figure 4). The mean values trendlines of FO1, FO2, and FO3 show an even greater ability to stabilize after the second generation and reach better fitness values (27.1, 97.2, and 0.6). The last 103 solutions suggest geometries with the largest shading areas. It is understood that overshading is not affecting the results negatively, but it is not necessary at the side of the already obstructed part of the analysis area. The contribution of the material area criterion is thus highlighted as a consideration in a microclimatic context with existing obstructions and when design variability and economy are desired.

5 SELECTION AND VERIFICATION

R2 is selected for further analysis as it is time-efficient, does not lack accuracy, and uses the material criterion as a regulator of excessive shading material. The objectives are prioritized as follows. UTCI and daylight are ranked higher, uniformity comes second, and the material area becomes the final indicator for selecting the solution that will be verified.

5.1 Filtering of Solutions and Evaluation

Further analysis of the simulations leads to selecting six solutions using Wallacei selection analysis methods: (1) The best-ranked solution for FO1 (UTCI): Gen. 17 | Indv. 2; (2) The best-ranked solution for FO2 (daylight): Gen. 14 | Indv. 1; (3) The best-ranked solution for FO3 (uniformity): Gen. 19 | Indv. 1; (4) The solution representing the relative difference between fitness ranks where ranking is set to 0 (best rank):

Gen. 14 | Indv. 5; (5) The solution representing the average of fitness ranks: Gen. 8 | Indv. 1; and (6) The best average solution of the last generation: Gen. 19 | Indv. 7.

The selected solutions are plotted on the PCP (Figure 5, left), exhibiting a good fit in UTCI (values under 27) and daylight (values above 90), a medium fit in uniformity (values between 0.58 and 0.71), and a medium to low fit in the material area (values between 50 and 100). The entire population is mapped on the objective space (Figure 5, right). This graph remaps the fitness values outputted by the simulation. FOs 1, 2 and 3 are display on the X, Y, and Z axes, respectively, and FO 4 is displayed through color (Green (fittest) to Red (least fit). The selected solutions are highlighted in Blue.

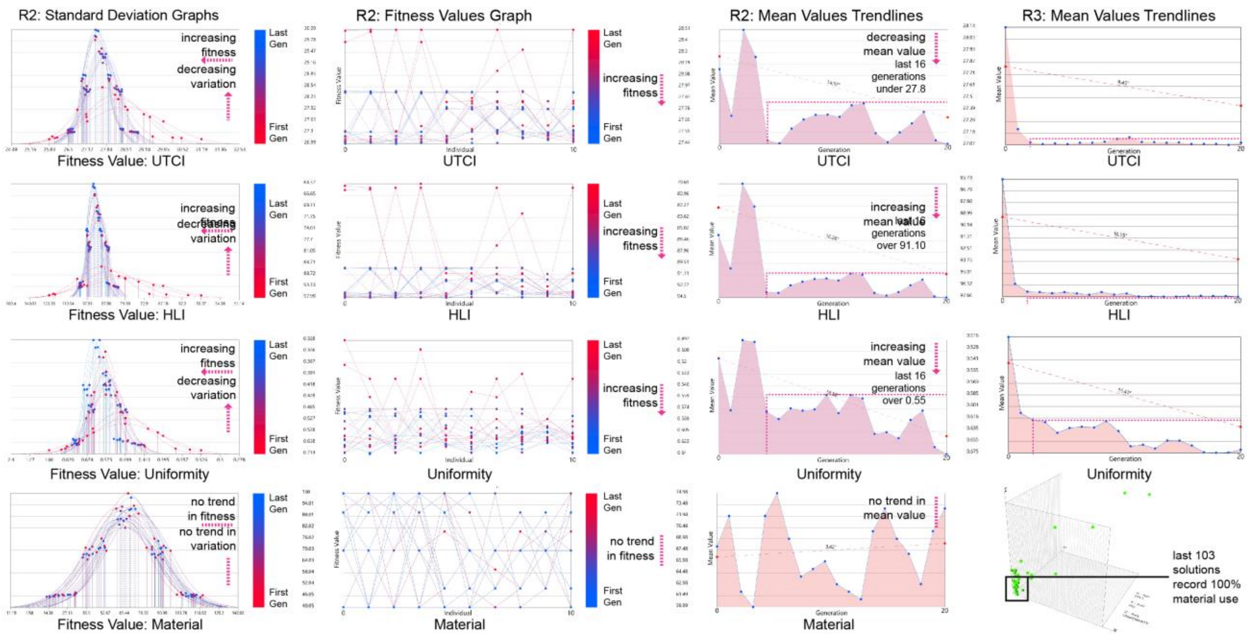

Figure 4: Standard deviation graphs, fitness values graphs, and mean values trendlines for the four FOs.

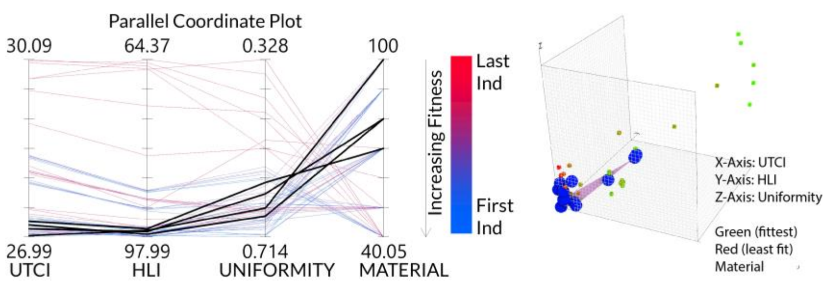

Figure 5: Parallel Coordinate Plot of R2 with the selected solutions being highlighted (left). The objective space of all the populations and the selected solutions are highlighted in Blue (right).

The phenotypes with their diamond fitness charts for all selected solutions can be seen in Figure 6, where fitness values and ranking for each objective are listed. The diamond fitness charts compare how well the different fitness objectives for this specific solution count; the closer to the center of the chart each objective appears, the fitter that objective is. The generative outdoor shading design shows significant design variability among the solutions achieved, occasionally without substantial differences in performative results. This multiobjective evaluation does not offer an 'all fit' single solution but rather a design direction at the early design stages. By removing shading material or elevating tiles to create permeability, most selected solutions suggest a denser core that dissolves towards the southern and the western side where the existing obstructions are (Figure 6).

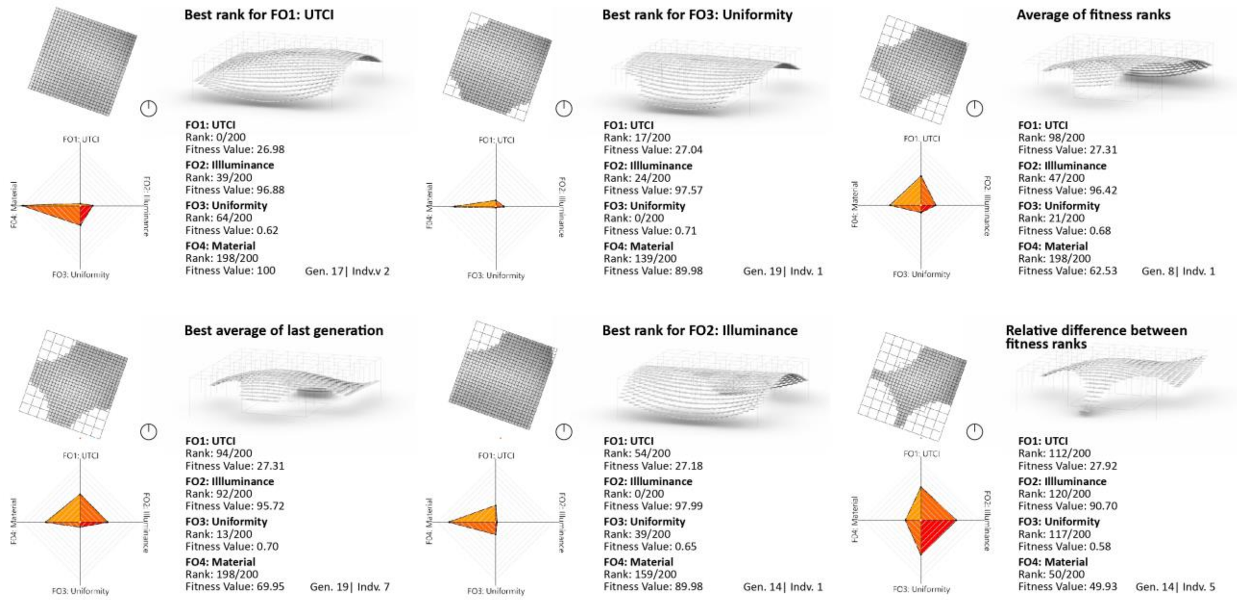

Figure 6: Grid with selected solutions: phenotypes, diamond fitness charts, and fitness values.

5.2 Verification of results

The solution selected for verification is the average fitness of ranks, generation 8, individual 1. The verification process involves the test of the three environmental objectives (UTCI, HIL, and uniformity) at three point-in-time simulations (9 am, 12 pm, and 3 pm) during a typical summer day (July 22). It is compared to a condition with no shading and a conventional horizontal canopy design positioned directly above the desired shaded area, a method commonly used as outdoor shelter. Daylight simulations use CIE sky type sunny with sun. It is noted that the coverage achieved with the proposed methodology is better within the evaluated area compared to the conventional horizontal shading (Figure 7).

More specifically, the optimized structure provides better shading with average UTCI levels between 37ºC and 42ºC, an average of 2K reduction compared to conventional shading, and an average of 6.7K reduction compared to the no shading scenario. Illuminance levels remain closer to comfort and with better uniformity across the evaluated surface. Median illuminance levels drop drastically in the morning hours from over 50,000lux without shading to a little over 5,000lux with conventional shading and a little over 3,000lux with optimized shading. Uniformity shows similar trend with more pronounced increase in the morning from 0.07 to 0.77 and the rest of the day from 0.7 to 0.84.

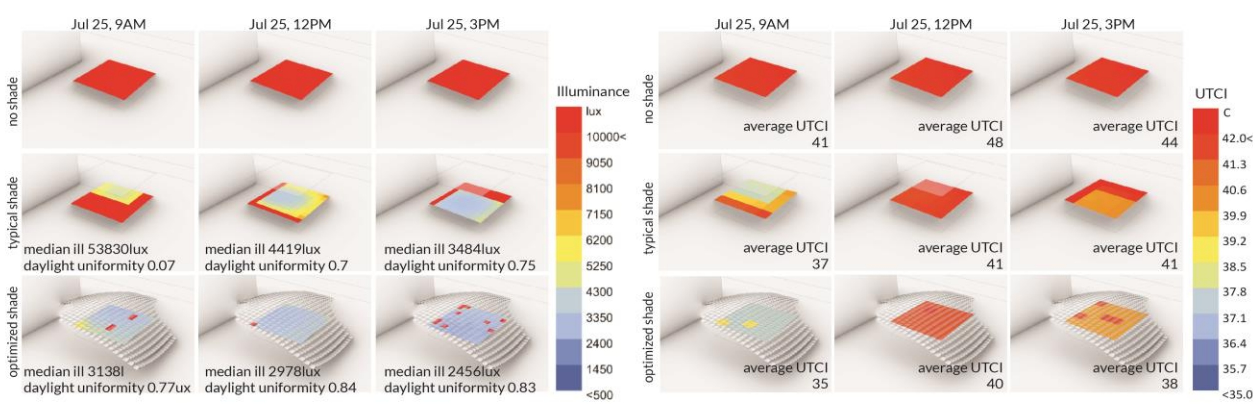

Figure 7: Left - Solution 2 UTCI compared to no shading and conventional shading design; Right - Solution 2 illuminance and daylight uniformity compared to no shading and traditional shading design.

6 DISCUSSION

The presented methodology offers a dynamic way to evaluate and optimize outdoor shading designs during early design stages and consists of a novel attempt to find a balance between the different thermal and daylight indices for such an outdoor educational setting. Refining the computational time and carefully defining the fitness objectives assisted in developing an efficient and effective methodology focused on optimizing the environmental performance while considering material use economy.

Applications that can benefit from this methodology include an early design guideline for outdoor shading, exposed or partially shaded areas in dense urban settings, and multiple shaded spaces that use the same design 'language' but vary based on microclimatic conditions. Any geometrical operation or material optical property of the tested shading design that can be parametrized to give different growth patterns and permeability can be included in the input genes. The demonstrated example is set in a sub-tropical climate that suggests shading as an effective strategy. However, the methodology is climate independent, as long as the need for shading is justified. The only parameter that needs adjustment per (micro)climatic context is the cooling period for testing UTCI.

Thermal and visual performance in the outdoors is the primary driver of the presented methodology; however, we acknowledge the flexibility of people to adapt themselves as long as a variety of spatial and environmental configurations are offered. The presented approach uses average values over the tested periods, and therefore, it is not expected to be uniformly effective during the shading period. However, operational and maintenance logistics, costs, and risks associated with movable structures eliminated this possibility.

There are several limitations associated with this methodology worth noting. Daylight assessment in the outdoors is based on limited research not developed adequately. Furthermore, the MRT input for the calculation of the UTCI is based on approximations that derive from not calculating the longwave radiation exchanges, and the shading material is assumed not to have thermal properties that participate in any thermal exchanges. Another limitation is that airspeed is taken from the weather as air movement has a lower impact on perceived outdoor thermal comfort than the MRT based on the literature review. In addition, Computational Fluid Dynamic (CFD) simulations require time that prohibits the evolutionary solver from computing multiple iterations for extended periods within a standard time expectation and produce valuable results for the defined time. However, it is acknowledged that CFD analysis would more accurately contribute to calculating UTCI, especially in temperate climates where air movement may be more critical. Another limitation is that UTCI is a static index that does not recognize the inertial effects of heat, while physiological parameters are considered static. Finally, evaporation and transpiration are not considered if vegetation is existent.

As simulation methodologies are optimized in accuracy and in the time needed to be performed -with integrated solutions that do not use fragmented simulation engines and cloud applications becoming increasingly accessible- this analysis can be refined, more reliable, user-friendlier, and faster. The genetic algorithm process is highly dependent on the granularity and accuracy of the input parameters. The selection process can be considered a comparative analysis that guides early-stage design decisions, and further improvement of the single selected solution is recommended. The constructibility of the shading design would also benefit from the inclusion of additional FOs that address structural performance and assembling.

7 CONCLUSION

There are numerous physical, mental, and cognitive benefits associated with spending time outdoors. The COVID-19 pandemic outbreak in the US at the beginning of 2020 was followed by increasing studies, investments, and proposals that enhance the quality of outdoor spaces within the ever-densifying urban fabric. After a detailed review of outdoor thermal comfort theories and indices, and after discussing the importance of accounting for the otherwise overlooked criterion of daylight in the outdoors, this paper presents a methodology to design an outdoor shading structure aimed to be used as an outdoor classroom that is responsive to thermal and visual comfort criteria. The tools used are validated simulation engines and a genetic algorithm software that permitted optimization of the design criteria.

The multiobjective evaluation tests multiple simulations to select the best-performing solutions. The input parameters, the structure and length of genes, the evaluation criteria, and the selection process consist of combined generative design and manual assessment. The evaluation of the predominant design solution revealed that the proposed methodology could substantially enhance the thermal and visual comfort within the defined area compared to a conventional horizontal shading device. Although there is great design variability in similarly performing options, the analysis revealed the genome trends of the best performing solutions that act as design guidelines during early design phases.

Future research will focus on developing the script to reduce run time and inclusion of structural and fabrication assessment criteria (objectives). Furthermore, testing different designs and different (micro)climatic settings will reveal the potential of this methodology, that together with post-simulation genome analysis, will allow identification of dominating or more repeated patterns.

ACKNOWLEDGMENTS

This work was supported by the University of Houston Division of Research (DOR) New Faculty Research Award 2021.

REFERENCES

Alrubaih, M. S., M. F. M. Zain, M. A. Alghoul, N. L. N. Ibrahim, M. A. Shameri, and Omkalthum Elayeb. 2013. "Research and development on aspects of daylighting fundamentals." *Renewable and Sustainable Energy Reviews, vol. 21*, pp. 494-505. doi: https://doi.org/10.1016/j.rser.2012.12.057.

Belcher, S. E., J. N. Hacker, and D. S. Powell. 2005. "Constructing design weather data for future climates." *Building Services Engineering Research and Technology*, vol. 26(1), pp. 49-61. doi: 10.1191/0143624405bt112oa.

Belosi, F., M. Conte, V. Gianelle, G. Santachiara, and D. Contini. 2021. "On the concentration of SARS-CoV-2 in outdoor air and the interaction with pre-existing atmospheric particles." *Environ Res* vol. 193, p. 110603. doi: 10.1016/j.envres.2020.110603.

Brown, R. D., and T. J. Gillespie. 1986. "Estimating Outdoor Thermal Comfort Using a Cylindrical Radiation Thermometer and an Energy Budget Model." *International Journal of Biometeorology*, vol. 30 (1), pp. 43-52. doi: Doi 10.1007/Bf02192058.

Chi, D. A., E. González M., R. Valdivia, and E. Gutiérrez J. 2021. "Parametric Design and Comfort Optimization of Dynamic Shading Structures." *Sustainability*, vol. 13 (14), p. 7670.

de Dear, R. and J. PIckup. 2000. "An outdoor thermal comfort index (Out_SET*)–Part 1–The model and its assumptions." In *Biometeorology and urban climatology at the turn of the millenium. Selected papers from the Conference ICB-ICUC*, vol. 99, pp. 279-283.

de Dear, R., G .Jendritzky, P. Weihs, E. Batchvarova, and G. Havenith. 2008. *"The universal thermal climate index UTCI: Goal and state of COST Action 730 and ISB Commission 6"*. In *Proceedings 18th Int. Congress Biometeorology ICB*, pp. 22-26.

Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan. 2002. "A fast and elitist multiobjective genetic algorithm: NSGA-II." *IEEE Transactions on Evolutionary Computation, vol.* 6 (2), pp.182-197.

Echouffo-Tcheugui, J. B., S. C. Conner, J. J. Himali, P. Maillard, C. S. DeCarli, A. S. Beiser, R. S. Vasan, and S. Seshadri. 2018. "Circulating cortisol and cognitive and structural brain measures." *The Framingham Heart Study, Neurology*, vol. 91 (21), pp. e1961-e1970.

Fägerstam, E. and J. Samuelsson. 2014. "Learning arithmetic outdoors in junior high school – influence on performance and self-regulating skills." *Education 3-13* 42 (4), pp. 419-431.

Göçer, Ö., K. Göçer, B. Özcan, M. Bakovic, and M. F. Kıraç. 2019. "Pedestrian tracking in outdoor spaces of a suburban university campus for the investigation of occupancy patterns." *Sustainable Cities and Society*, vol. 45, pp. 131-142. doi: https://doi.org/10.1016/j.scs.2018.11.006.

Grima, N., W. Corcoran, C. Hill-James, B. Langton, H. Sommer, and B. Fisher. 2020. "The importance of urban natural areas and urban ecosystem services during the COVID-19 pandemic." *PLOS ONE* 15 (12)e0243344. .

Gustafsson, P. E., A. Szczepanski, N. Nelson, and P. A. Gustafsson. 2012. "Effects of an outdoor education intervention on the mental health of schoolchildren." *Journal of Adventure Education and Outdoor Learning* vol. 12 (1), pp. 63-79.

Hartmeyer, R., and E. Mygind. 2016. "A retrospective study of social relations in a Danish primary school class taught in 'udeskole'." *Journal of Adventure Education and Outdoor Learning*, vol. 16 (1), pp. 78-89.

Höppe, P. 1999. "The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment." *International Journal of Biometeorology*, vol. 43 (2), pp. 71-75.

Hwang, R. L., and T. P. Lin. 2007. "Thermal Comfort Requirements for Occupants of Semi-Outdoor and Outdoor Environments in Hot-Humid Regions." *Architectural Science Review*, vol. 50 (4), pp. 357-364.

Kuo, M., M. H. E. M. Browning, and M. L. Penner. 2018. "Do Lessons in Nature Boost Subsequent Classroom Engagement? Refueling Students in Flight." *Frontiers in Psychology* 8 (2253).

Lai, D., Z. Lian, W. Liu, C. Guo, W. Liu, K. Liu, and Q. Chen. 2020. "A comprehensive review of thermal comfort studies in urban open spaces." *Science of The Total Environment* 742, p. 140092. doi: https://doi.org/10.1016/j.scitotenv.2020.140092.

Lin, T. P. 2009. "Thermal perception, adaptation and attendance in a public square in hot and humid regions." *Building and Environment*, vol. 44(10), pp. 2017-2026. doi: https://doi.org/10.1016/j.buildenv.2009.02.004.

Liu, W., Y. Zhang, and Q. Deng. 2016. "The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate." *Energy and Buildings*, vol. 128, pp. 190-197. doi: https://doi.org/10.1016/j.enbuild.2016.06.086.

Mackey, C., T. Galanos, L. Norford, and M. Roudsari. 2017. "Wind , Sun , Surface Temperature , and Heat Island : Critical Variables for High-Resolution Outdoor Thermal Comfort."

Mackey, C., M. Sadeghipour Roudsari, and P. Samaras. 2015. "ComfortCover: a novel method for the design of outdoor shades." Proceedings of the Symposium on Simulation for Architecture & Urban Design, Alexandria, Virginia.

Matzarakis, A., S. Muthers, and F. Rutz. 2014. "Application and comparison of UTCI and PET in temperate climate conditions." *Finisterra* 48, pp. 21-31.

Meredith, G. R., D. A. Rakow, E. R. B. Eldermire, C. G. Madsen, S. P. Shelley, and N. A. Sachs. 2020. "Minimum Time Dose in Nature to Positively Impact the Mental Health of College-Aged Students, and How to Measure It: A Scoping Review." *Frontiers in Psychology* 10 (2942).

Makki, M., M. Showkatbakhsh, Y. Song. 2019. Wallacei Primer 2.0 [online].

Morse, J. W., T. M. Gladkikh, D. M. Hackenburg, and R. K. Gould. 2020. "COVID-19 and human-nature relationships: Vermonters' activities in nature and associated nonmaterial values during the pandemic." *PLOS ONE* 15 (12)p. e0243697.

Mygind, E. 2007. "A comparison between children's physical activity levels at school and learning in an outdoor environment." *Journal of Adventure Education and Outdoor Learning* 7 (2), pp. 161-176. doi: 10.1080/14729670701717580.

Naboni, E. 2014. *Integration of Outdoor Thermal and Visual Comfort in Parametric Design*.

Ng, E., and V. Cheng. 2012. "Urban human thermal comfort in hot and humid Hong Kong." *Energy and Buildings* 55, pp. 51-65.

Nikolopoulou, M. 2011. "Outdoor thermal comfort." *Frontiers in bioscience (Scholar edition)* 3, pp. 1552-68. doi: 10.2741/245.

Nikolopoulou, M. and S. Lykoudis. 2006. "Thermal comfort in outdoor urban spaces: Analysis across different European countries." *Building and Environment* 41 (11), pp.1455-1470.

Pan, W. and J. Du. 2021. "Effects of neighbourhood morphological characteristics on outdoor daylight and insights for sustainable urban design." *Journal of Asian Architecture and Building Engineering*, pp. 1-26. doi: 10.1080/13467581.2020.1870472.

Razani, N., K. Niknam, N. M. Wells, D. Thompson, N. K. Hills, G. Kennedy, R. Gilgoff, and G. W. Rutherford. 2019. "Clinic and park partnerships for childhood resilience: A prospective study of park prescriptions." *Health Place*, vol. 57, pp. 179-185. doi: 10.1016/j.healthplace.2019.04.008.

Rodono, G., E. Naboni, V. Sapienza, F. Cucchi, and G. Macrelli. 2020. "Simulation Workflow for Parametric Optimization of Outdoor Comfort-Based Origami Shelter." *Journal of Architectural Engineering*, vol. 26 (3), p. 04020022.

Rodonò, G., E. Naboni, V. Sapienza, F. Cucchi, and G. Macrelli. 2020. "Simulation Workflow for Parametric Optimization of Outdoor Comfort-Based Origami Shelter." *Journal of Architectural Engineering*, vol. 26 (3), pp. 04020022.

Sadeghipour Roudsari, M., and M. Pak. 2013. "Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design." *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, pp. 3128-3135.

Shih, W. M., T. P. Lin, N. X Tan, and M. H. Liu. 2017. "Long-term perceptions of outdoor thermal environments in an elementary school in a hot-humid climate." *International Journal of Biometeorology*, vol. 61 (9), pp. 1657-1666. doi: 10.1007/s00484-017-1345-x.

Spagnolo, J., and R. de Dear. 2003. "A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia." *Building and Environment* 38 (5), pp. 721-738. doi: https://doi.org/10.1016/S0360-1323(02)00209-3.

Tregenza, P. and I. Waters. 1983. "Daylight coefficients." *Lighting Research & Technology - LIGHTING RES TECHNOL* 15, pp. 65-71. doi: 10.1177/096032718301500201.

Tseliou, A. I. X. Tsiros, M. Nikolopoulou, and G. Papadopoulos. 2016. "Outdoor thermal sensation in a Mediterranean climate (Athens): The effect of selected microclimatic parameters." *Architectural Science Review* 59 (3), pp. 190-202. doi: 10.1080/00038628.2015.1028022.

Ward, G. J. 1994. "The RADIANCE Lighting Simulation and Rendering System." *Siggraph '94*, pp. 459–472. doi: 10.1145/192161.192286.

Yang, W., N. H. Wong, and S. K. Jusuf. 2013. "Thermal comfort in outdoor urban spaces in Singapore." *Building and Environment* 59, pp. 426-435. doi: https://doi.org/10.1016/j.buildenv.2012.09.008.

Zhang, L., D. Wei, Y. Hou, J. Du, Z. Liu, G. Zhang, and L. Shi. 2020. "Outdoor Thermal Comfort of Urban Park—A Case Study." *Sustainability*, vol. 12 (5), p. 1961.

AUTHOR BIOGRAPHY

MILI KYROPOULOU is an Assistant Professor at the Gerald D. Hines College of Architecture and Design. She holds a MSc in Sustainable Environmental Design from the AA in London. Her research interests include building performance simulations, computational design, generative design, human-centric design, performance-based design, performance parametrics, and solar form-finding. Her email address is mkyropoulou@uh.edu.