PERFORMATIVE SHADING DESIGN

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Today's building stock accounts for 48.7% of the total energy consumption in the United States, and the building enclosure is one of the largest determinants of energy consumption.[1] The role of the facade is to maintain the comfort and security of the interior against the outside environment. Regulation of temperature, protection from sound, excess sunlight, pollution and other environmental factors are all encompassed in the role of the building envelope. In addition to maintaining thermal and visual comfort of the interior, the facade also provides a visual link to the environment. Through these responsibilities the facade directly influences the energy consumption of a building's mechanical systems, such as air conditioning, furnaces and artificial lighting.

In order to meet the challenges of energy saving initiatives and codes such as Architecture 2030, California Title 24 and ASHRAE 90.1, the building facade must be carefully designed to minimize energy consumption. However, the effectiveness of a facade system is not entirely based on minimizing energy usage; solar and visual considerations such as glare and the preservation of views to the exterior are also important. The performance of a facade system can therefore be defined as a combination of thermal and visual comfort, which in turn means energy savings as a result of reduced heating, cooling loads and artificial lighting. In particular, the scope of this research focuses on solar considerations as the performance metric, covering solar radiation passing through the facade, regulating and maintaining natural light into the interior, and minimizing discomforting glare.

Highly glazed enclosures offer excellent views and allow large amounts of natural light to enter a space, reducing the need for artificial lighting and saving energy. However, too much light may introduce excessive heat gains and the possibility of uncomfortable glare. While a reduction on glazing area may limit heat gains and reduce glare, it may also increase the use of artificial lighting due to lack of natural light. One method to moderate solar metrics (solar radiation, daylighting and glare) while still preserving views is by integrating a shading system into the facade. Shading devices such as overhangs, fins and louvers are able to be custom designed to perform in different climates, orientations and timeframes, providing excellent solar control.

DESIGN

The conceptual design stage of a building is often one of the most important stages. The decisions made here greatly affect the overall outcome, and it is critical that accurate and informed choices are made. Current means of developing designs and design alternatives of shading systems focus on generating small, manageable working sets of designs and basing decisions off of those original concepts.[2] These designs are analyzed, reviewed and adjusted accordingly, but are limited by only starting with a small sample size of design alternatives. Furthermore, analysis is generally performed individually on each option, therefore extra options require more time and resources to narrow down options and search for the most effective system.

Increasing design iterations and alternatives can provide a higher likelihood of finding effectively performing designs.[2] Parametric modeling incorporates defined characteristics of a design into a variable, allowing changes to be made to specific portions of a model quickly and in a controlled environment. The parameterization of a conceptual design can lead to a generative exploration of design alternatives. Once design intentions have been digitized via parameters, the parametric model can be continually adjusted to produce alternative designs that follow the constraints of the project, as well as the direction and intents of the designer.

SOFTWARE PLATFORM

Rhinoceros 4.0 SR9 with the Grasshopper 0.9.0014 plug-in were used as the main software platforms for this study. Two external and one internal plug-ins for Grasshopper were used as the simulating engine, optimization solver, and data exporter. DIVA 2.0.1.0 with component version 2.0.0.6 functioned as the simulation engine, calling upon Daysim and Radiance to perform the climate-based illuminance and radiation calculations. Galapagos was used as the single-objective optimization solver, using its built-in genetic algorithm. Lunchbox 0.35, a multi-functional plug-in developed by Nathan Miller, enables Grasshopper to collect and export data into Excel sheets as well as read back Excel data for re-instantiation.

PARAMETRIC DEFINITION

The process definition built in Grasshopper consists of six different pieces:

- Inputs: geometry, materials, directional vectors, sensor placement and climate data
- Parameters: shading system configuration parameters (glazing type, number of louvers, louver length and angle, number of fins, fin length and angle, horizontal and vertical offset)
- Measurements: daylight performance measurements (solar radiation, uniform daylight illuminance (UDI), simplified daylight glare probability (DGP))
- Optimization: evolutionary solver and metric weighting factors
- Data: collecting, sorting and exporting completed simulation data
- Re-instantiation: visualizing and displaying simulation results

The results of the process definition are a compiled data set of shading system configurations, the corresponding performance measurements, and a visual representation of each system setup.

Ten scenarios were tested using the process definition – comparing different typologies, timeframes, orientations and weighting factors. Each comparison was done to examine how the optimum shading system parameters would change as the simulation conditions changed. The sensitivity of each parameter would correspondingly change as the conditions for the simulations were altered, highlighting how each parameter reacts to particular changes.

The user inputs for the definition consist of selecting the rooms that are to be analyzed, the surrounding context buildings, and appropriate climate data. Localized axes are derived from the room geometries to address directionality inside the Grasshopper interface. Sensors for measuring solar radiation daylighting, and glare use the local axes to find their positions inside the rooms. All the inputs are designed to easily integrate any project for analysis, requiring only the minimal user setup before getting started.

In order to maintain a realistic scenario for testing, a developing building design was chosen to serve as the reference building. More importantly, a project with a high amount of surface area exposed to the sun and different programmatic spaces housed inside the building was especially desirable (e.g., a skyscraper). A 70 story tower oriented towards the southwest and featuring a tapering and curving southern facade was chosen as the reference building. A three story podium houses hotel amenities and retail spaces, while the lower portion of the tower consists of both creative (open plan) and standard office layouts (closed offices). The upper two thirds of the building used for hotel rooms with the top including a sky lobby, restaurant, and pool area.

Three rooms were modeled from the reference building's typical plans: a hotel room on the 35th floor, an open plan office, and standard enclosed office on the 15th floor. The hotel was modeled as a 14'-4" by 28'-6" room with 9'-8" ceilings and a small notch in the back, indicating the enclosed bathroom area. The open office was modeled as a large 30' by 30' unobstructed space with 10' ceilings. The office area extends all the way to the service core of the building, 30' away from the glass facade. An additional open office was modeled on the eastern facade for the multiple orientation comparison scenarios. The closed office was modeled around the perimeter of the glass facade as a small 10'-3" by 15' room with 10' ceilings. All rooms were located in the middle of the facade they were oriented towards.

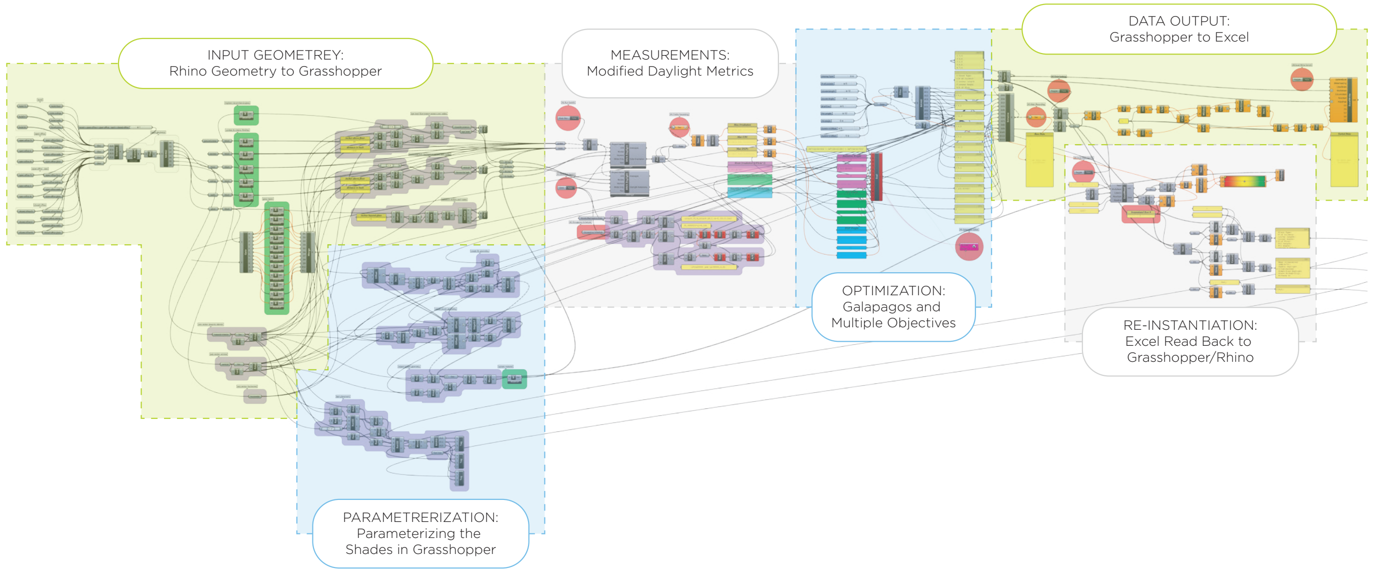


FIGURE 1
Grasshopper routine indicating the six separate pieces that make-up the process.

Each room is broken down into components, based on their respective materials – ceilings, floors, walls, and glass. In addition to the individual room components, the surrounding context buildings in a three block radius are accounted for, along with the ground surface. Each of these components must be assigned a material that carefully matches the actual reflectivity of the material.

In addition to the material selection of the geometrical components, each room needed to include a set of three vectors that indicate directionality within the space. Three lines are drawn to represent each direction, or in the context of the analyzed space, horizontal, vertical and towards interior directions. These vectors are unique to each room and need to be drawn up for each space. With these vectors in place, Grasshopper will be able to know which direction is up and down, where to place daylight and irradiation sensors, and how to manipulate the shading system parameters.

Nine parameters were developed to control the shading system configuration. The parameters were designed to include a large range of variation and be as flexible as possible to avoid minimizing the exploration space of the optimization routine. The parameters focus on glazing properties, the number and physical properties of louvers and fins, and the position of the entire system from the building face.

There are two phases in which the simulations are conducted: a preliminary run that simulates and stores data for the optimization equation performed later, and the main run, which runs continuously and records all data for exporting. The preliminary set attempts to build a maximum scenario based on the given inputs and parameters. For example, introducing the maximum amount of radiation, highest percentage of UDI, and highest DGPs. To achieve the maximum scenario, the shading system is turned off allowing light and radiation to enter the space and hit the sensors without any obstructions. The preliminary run is only done once at the beginning of each simulation sequence. The main run includes all scene geometry with materials applied, contextual surrounding geometry, and shading device geometry. The main simulation is connected to Galapagos, which continuously runs simulations as it attempts to find an optimum solution.

Within the preliminary and main phase run, two different types of simulations are run; one measuring solar radiation, and the other measuring illuminance (with a horizontal sensor at the work plane and a vertical sensor eye-level). Each simulation component requires four things: (1) geometrical components of the room to be measured with the proper DIVA materials applied, (2) the location of each analysis node, (3) the vector direction of each analysis node, (4) a switch that enables or disables the simulation from running. The switch is used to control the different phases of simulations, as well as disabling simulations from running as changes are made to the geometry, parameters, analysis nodes, etc.

Once the preliminary simulation and an initial main simulation have been completed successfully, the process is calibrated and ready to begin optimizing different configurations. Galapagos functions as the solving component. All parameters are plugged into the Galapagos to be flexed during the solving process. One of Galapagos' limitations is its ability to only solve one objective at a time. This objective is achieved by minimizing or maximizing a single fitness number. While native Galapagos is limited to single objective optimizations, multiple objectives can be solved for, but require a separate precursor process – an equation to condense multiple objectives into a singular fitness number.

The condensed fitness objective can be defined as a function of the sum of the each objective (measurement). Each metric is either positive or negative based on if the goal is to minimize or maximize that particular metric. In this case, a combination of minimizing solar radiation (negative), maximizing UDI (positive), and minimizing glare (negative) is applied to the new pseudo multi-objective fitness equation. Additionally, to ensure each metric is equally measured against each other, the measurements going into the equation are normalized to a 0 to 1 scale. The maximum conditions measured and stored from the preliminary run are fed into the normalizing process.

SIMULATIONS

With the greatest solar exposure at the southwest, it was deemed to be the main area of focus for the simulations. All testing was conducted with the room facing south, unless otherwise noted. All simulations were conducted over the course of a year (January 1st to December 31st), concentrating on testing the effectiveness of the static shading system year round rather than on any particular dates or timeframes. Furthermore, all performance metrics were valued as equal by default, with the ability to change the significance of each metric as needed.

The preliminary/baseline scenario analyzed the open office space, facing south and throughout an entire year. The hotel and closed office was analyzed under the same conditions to compare the typologies against each other. The comparison of the three spaces examines how the shading system configures to adapt to the different sizes and occupied times of each room. The baseline scenario was then compared against two different timeframes – one month during the winter (December 21st to January 21st) and one month during the summer (June 21st to July 21st). Narrowing the simulation time examines how the shading system configuration might be optimized for those particular times of the year in contrast to an annual simulation.

To examine the effect orientation has on the shading system and its corresponding parameters, an east facing office was simulated. An identical size and sensor layout open plan office was used to simulate the eastern facing office. Both scenarios were conducted over the entire year.

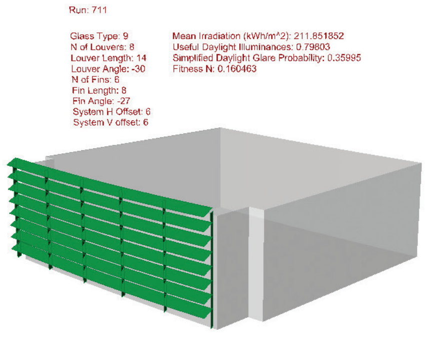
Lastly, the baseline was compared against two sets of scenarios with varying performance valuing (weighting) during the optimization evaluation sequence. The baseline simulation equally valued each performance metric (solar radiation, UDI, DGPs). A set of simulations, changing the significance of UDI by a factor of 2 and 3, respectively, were conducted to investigate the shading system configuration and parameter response by altering which performance metrics were deemed more important. The second comparison altered the value of the modified DGPs metric by factors of 2 and 3 also. Each part of the process definition can be changed or disabled by the user. The entire process was kept open source to allow for customization of any inputs, parameters, equations or weighting factors.

DATA

During the course of the optimization process, all data is continuously recorded before being exported to Excel for analysis and graphical representation. Each parameter setting, all three daylight metrics, and the overall fitness number is recorded. Once the optimization process has completed an appropriate number of generations or relative convergence is reached, the solver ends and the data stops being recorded.

The data is then exported to a pre-formatted Excel template. The template has color coding for the fitness values to indicate the more desirable shading system configurations. Additionally, the Excel template includes a LINEST function that performs linear regression on the

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Glass Type	N of Louve	Louver Le	Louver An	N of Fins	Fin Length	Fin Angle	System H	System V	Mean Irra	Useful Da	Simplified	Fitness	#
2	9	8	14	-30	6	8	-27	6	6	211.8519	0.79803	0.35995	0.160463	711
3	9	7	12	-33	5	8	-39	6	-6	212.6667	0.828681	0.425032	0.119264	1131
4	9	8	15	-30	6	8	-24	8	6	191.1111	0.870826	0.493522	0.118568	903
5	9	8	14	-30	7	8	-24	6	12	231.7531	0.816639	0.402319	0.104603	109
6	9	6	14	-30	6	8	-36	6	6	271.5556	0.819923	0.358854	0.100513	975
7	9	8	14	-30	6	8	-24	6	6	205.0617	0.727969	0.364912	0.088344	780
8	9	8	14	-30	7	9	-39	10	12	253.5062	0.83306	0.417255	0.074654	445
9	9	8	14	-30	7	8	-24	10	12	252.284	0.842365	0.428585	0.07374	1
10	9	7	14	-30	6	7	-36	6	-6	243.2716	0.889436	0.487787	0.071016	977
11	9	7	13	-36	6	7	-36	6	-6	270.642	0.766831	0.338168	0.067397	1069



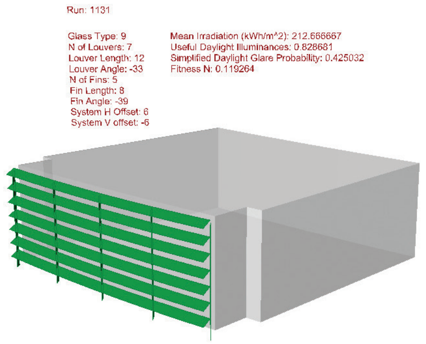


FIGURE 2
Top two performing configurations of the baseline open office.

FIGURE 3
Shading system configurations and parameter/measurement information for simulations #711 and #1131.

FIGURE 4
Significant parameters for the baseline open office.

FIGURE 5
Number of louvers and louver parameters examined for the baseline open office.

parameters versus the fitness value to indicate which parameters are considered statistically significant. Another sheet in the template has eight scatter plots prepared to display each of the parameters plotted against the fitness value.

FINDINGS

As outlined in the methodology, 10 unique scenarios were simulated, optimized and recorded for review.

- Typologies: hotel, open office and closed office
- Orientations: south and east
- Timeframes: annual, winter and summer
- Weighting: 1x, 2x, 3x weighting of UDI and 1x, 2x, 3x weighting of DGPs

These scenarios resulted in over 10,000 simulations being conducted, testing different shading system configurations' effectiveness against measured amounts of solar radiation, daylighting and glare probability. Due to the sheer number of parameters and scenarios analyzed, only two of the nine parameters are covered, and only the baseline open office space (facing south was simulated over the course of an entire year). The open office simulation was conducted with all performance metrics equal in value to each other during the optimization sequence.

After completing 1217 simulations, approximately 23 generations through Galapagos, a good range of configurations were documented. All the data is recorded and streamed into an Excel document template which is used to review each configuration as raw numerical data and graphically through scatter plots. All nine parameters are recorded along with the mean irradiance values, useful daylight illuminances, simplified daylight glare probability, derived fitness value, and the simulation run number. Simulations #711 and #1131 rank as the top two most effective shading system configuration based on the combined performance fitness evaluation formula. Minor differences exist between #711 and #1131, but most parameters are within the same end of each parameter range. Both configurations include a high number of louvers with medium depth and a strong negative angle. They have a middle amount of fins with a short depth and also a strong negative angle. Both systems are offset in both directions a few inches off the face of the building.

The Number of Louvers parameter follows a fairly steep convex trend line. A convex trend line indicates that somewhere in the middle of the parameter range is the best configuration, and in this case the curve reaches its peak at eight louvers. Before and after eight louvers the trend line slopes downwards, signifying a loss of fitness and a less optimal parameter choice. The Louver Length parameter has a larger convex trend line, further demonstrating how the fitness values react as the length of the louver is changed. A short louver depth has a poor fitness value, but too deep a louver is also undesired. A range between 12 to 16 inches for the louver length achieves the highest fitness values.

Both parameters exhibit trends that highlight the usefulness of this process. Given the range for these parameters, too low or too high produces a suboptimal fitness value, but a number somewhere in the middle – in which the process helps to narrow down and locate – is the most effective configuration.

CONCLUSION

A design process that can help guide designers to make informed and effective decisions regarding shading systems can improve energy efficiency and occupant comfort. This research focused on a design process which constructed a parametric shading system and optimized the system based on three solar-based metrics. The entire process is open source and allows the user to manipulate many pieces of the workflow, including which metrics are possibly more important to the design than others, and skew the optimization towards catering to that measurement.

The process produces two sets of information: a list of optimized shading system configurations based on user inputs, design constraints, and metric weighting, and graphical representations of how each parameter influenced the overall performance of the system. The results highlight the impact of each parameter and potentially which variables of the parametric shading system should be focused on for design alternatives. This workflow can be used as a tool for designers to narrow down and focus their designs, guiding their designs with informed decisions.

P	Q	R	S	T	U	V	W	X	Y
1217	0.014774	1.51E-17	1.51E-11	0.094465	0.001504	6.38E-71	3.37E-23	2.7E-53	
	System V	System H	Fin Angle	Fin Length	N of Fins	Louver An	Louver Le	N of Louvers	
	-0.00071	-0.00855	-0.00212	0.001967	0.009697	-0.00555	0.014325	0.048594	-1.00693
	0.000291	0.000987	0.000311	0.001175	0.003048	0.000291	0.001414	0.003008	0.027723
	0.598436	0.128143	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
	224.843	1207	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
	29.53642	19.81964	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A