Design optimization of building fixed shading using an integrated tool of EnergyPlus and Dakota

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ABSTRACT

Building fixed shading design requires many aspects to be considered simultaneously, i.e. illumination comfort, heat gain, daylighting, natural ventilation. This difficult process involves adjusting the size, number, reflectance, angle and position of the fixed shading to explore the variables area and find the optimal design. The following study proposes an integrated tool of EnergyPlus and Dakota, a generic optimization engine, which are embedded into Legacy OpenStudio. The illumination comfort, heat gain and daylighting are calculated by EnergyPlus without consideration of the ventilation performance. Furthermore, a multi-objective of solar heat gain and useful daylight illuminance optimization design process is applied to a one zone room to optimize the south window's fixed shading. The results show that the integrated tool can help designers explore the design options and have a quick and easy fulfillment of their objectives in the early design stage.

KEYWORDS

fixed shading design, optimization, building energy efficiency, daylighting

INTRODUCTION

With the development of green building rating systems and demands of decrease building energy consumption, building energy efficiency (BEE) design is concerned by government, clients and researchers across the world. Green building rating systems mark BEE the biggest parts, for example 19%-24% total points in China green building assessment standard (MoC 2014). So how can we design an energy efficiency building? Designers adapt passive or active BEE design strategies to improve buildings' energy performance. Improvement of building envelope is categorized as passive design strategies which will increase the indoor thermal comfort, decrease the heating and cooling load resulting to a small size of HVAC system and operation energy. So passive building design is a priority of the whole building efficiency design.

Building envelope components of walls, fenestrations, roofs, shadings etc. keep the indoor and outdoor environments apart. Among all of the envelope components, design of fixed shading is the most difficult one which requires many aspects to be considered simultaneously, i.e. illumination comfort, heat gain, daylighting, natural ventilation. This difficult process involves adjusting the size, number, reflectance, angle and position of the fixed shading devices to explore the variables domain and find the optimal design. BEE design and optimization technique is the right method to solve this knotty problem. Wetter (2005) optimized the passive design of a three thermal zones office building using five independent variables, i.e. depth of south, north window, the overhang of south window and two shading control setpoints. Torres and Sakamoto (2007) set 21 variable parameters including the size, number, optical properties of the window and shading slat when optimizing an uncommon exterior window fixed shading using Radiance as the simulation engine. The optimization goal set to the maximum energy savings taking reduction of daylight discomfort and daylight penetration into consideration, however this study did not use any energy simulation software yet. Andersen et al. (2008) proposed a daylighting design approach called Lightsolve which highlights using dynamic daylighting metrics, time-segmented method, Spatio-Temporal Irradiation Maps (STIMAPs) as the main methods, and the expert design support system and optimization module were underlying developing. Gagne and Andersen (2010) presented an optimization method based on the genetic algorithm (GA) and Lightsolve Viewer, a daylighting calculation engine which helps explore the façade design variables, relating to window size, position and transmissivity and shading devices and the transmission of the shading device. This research used illuminance and Daylighting Glare Probability (DGP) as the metrics. Manzan (2009, 2014 and 2015) carried out a GO optimization method to find out the optimal design of an external fixed shading device using DAYSIM calculating lighting loads and ESP-r calculating the energy consumption. ModeFRONTIER, a general commercial optimization tool, was used to drive the GO optimization iterative loop. Without using any optimization algorithms, OpenStudio Parametric Analysis Tool (PAT) (NREL 2016) is a parametric analysis module of OpenStudio which integrated EnergyPlus conducting energy simulation and radiance daylighting simulation.

Although there have been remarkable research outcomes, integrating these optimization methods into designer-friendly building modeling software, for example SketchUp, is still a work need to be done. It will bring academic research theory to building design industry.

The reminder of this paper is structured as follows: Section 2 describes the proposed design and optimization methodology. Section 3 provides an overhang design case study. In this section, optimization alternative variables, objective functions, optimization algorithm and results are presented. Section 4 concludes this research and finds out that the proposed design optimization method facilitates designers designing high performance fixed shading devices.

FIXED SHADING DESIGN AND OPTIMIZATION METHODOLOGY

Simulation and optimization method

In this study a designer-friendly simulation-based optimization scheme is implemented (Figure 1) to optimize building energy consumption in the early design stage. This integrated tool is a combination of EnergyPlus 8.4.0 (NREL 2015) and Dakota 6.3.0 (Sandia 2016), and is embedded into Legacy OpenStudio SketchUp Plugin (NREL 2011). EnergyPlus is a heat balance-based whole building energy simulation software that reads input and writes output to text files which make it easy to integrate with other software. To simulate daylight, EnergyPlus employs split-flux algorithm which treat complex geometries as planes which is less accurately than reverse ray-tracing algorithm (Jakubiec and Reinhart 2011). Though split-flux method has shortcomings, it can fulfil daylight analysis in most cases. Dakota is a design optimization software which also be used for parameter estimation, uncertainty quantification, and sensitivity analysis. Legacy OpenStudio is an extension of designer-friendly modeling tool of Trimble's SketchUp which allows users to quickly create geometry needed by EnergyPlus. As shows in Figure 1, the integration of EnergyPlus and Dakota is embedded into Legacy OpenStudio SketchUp Plugin and users do not have to know the inside technique detail. The optimization dialogs allow users to set up alternative variables, optimization algorithm and objective function. Legacy OpenStudio SketchUp Plugin reads the optimization results and gives the optimal or near-optimal designs. This integrated optimization tool works as follows:

1) Build building energy simulation model (baseline model).
2) Setup optimization variables, algorithms, objective functions.
3) Run simulation.
4) Read optimization results.

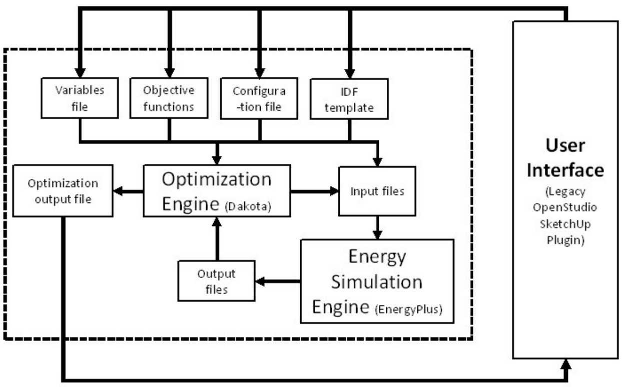

Figure 1. *Optimization function scheme*

Design analysis and optimization variables

Building fixed shadings not only shade sun-light, but also shape impressive building façade with designers' elaborative design. Typically, fixed shading devices include overhang device, vertical device and synthesis device. Shading device should be carefully designed to introduce solar into building in winter, impede daylight in summer with consideration of sustainable daylighting and visual comfort. An excellent shading design will decrease building heating and cooling load which further result to small size of HVAC system. Without powerful design-aided tools, it is impossible to take all these aspects into consideration.

To optimize the design of common fixed shadings, such as overhang and vertical shading device, shading slats depth, slats length, sill depth, distance with window frame, the angle with their base wall and the reflectance of slats are traded as the optimization variables, among which sill depth can be ignored since it has little impact on the whole performance of exterior windows.

Evaluation criteria

Introducing daylight into building causes manifold effects that range from aesthetics, solar heat gain, illumination comfort to energy saving of lighting. With consideration of all these effects, building performance simulation can help designer team design an occupancy health, comfort, energy saving for lighting and less heating/cooling load building. Building fixed shading not only affects building daylighting, but also affects building ventilation performance which is much more complex to predict

Any extra daylight which may cause overheating is undesired, while in winter we have a contrary preference. The less of cumulative transmitted solar heat gain in the summer period and the more in the winter period the better. The aggregate of solar heat gain is obviously a climate-based metrics. Excellent building passive design achieves low building heating and cooling load which then results small sizing of building HVAC system. As a climatic based metric, though not annual, heating/cooling load may be set as the criterion.

Oversupply of daylight results human sensation of visual discomfort. If one stays near the exterior south window, his common visual discomfort comes from view of exterior window and work table. Glare is used to quantitative weight visual discomfort. Annul Glare Index calculated by EnergyPlus is modified version of Cornell Daylight Index (DGI), so it does not consider direct light and specular reflection and cannot predict of discomfort glare of horizontal work area which is people's common visual experience. Threshold value of 2000 lux represents oversupply of daylight that may cause visual discomfort.

Daylight factor is a widely used metric to judge which design measures will enhance daylighting in a space. The drawbacks of daylight factor are that it doesn't take consideration of orientation, location, and climate. Climate-based daylight metrics perform the annual daylight performance depending on the standard meteorological year dataset. In order to assess annual daylight availability, climate-based annual massive data should be used as the metrics. If daylighting illuminance is high enough, for example 500lux, the artificial lights is allowed to switch dim or shut down, while the dim control mechanism of lights doesn't take oversupply daylighting into consideration. Though EnergyPlus adapt this dim control mechanism, it is not a desirable criterion. There are two most commonly used metrics: daylight autonomy (DA) and useful daylight illuminance (UDI). UDI takes a comprehensive consideration of useful level daylight and the propensity of oversupply daylight which are related with discomfort glare. In paper (Nabil et al. 2007) UDI uses the lower and upper thresholds of 100lux and 2000lux dividing the whole year working time into three bins. A case study of a four-story open-plan building with a central light-well with or without shading facades and light-well shows that UDI is the best daylight metrics comparing with Daylight Factor (DF) and DA (Mardaljevic and John 2007, Hensen and Lamberts 2011).

CASE STUDY

In the early design stage, designer's decisions have huge impact on buildings' shape. Traditionally, designers are accustomed to qualitative analysis based on their previous experiment and knowledge. To some extent, that is due to lack of powerful and easy-to-use analysis tool. In this study, an analysis of an office building with overhang was carried out to assess the usability of this proposed method and tools. The building locates at Nanjing, the capital city of Jiangsu province of China with a summer-hot-winter-cold climate.

Scene geometry

A detailed model is built including neighboring buildings and landscape, as Figure 2 shows. We also set the ground plane and assign it a material with a constant reflectance. The building surface materials' optical properties are careful examined and set. The analyzed room is at the sixth story of 7 stories building and all other room are omitted. The baseline overhang has a size of 2.45m for length, 0.9m for depth, 0.25m above the window and vertical with its base wall. The exterior window is double panel low-e coated window.

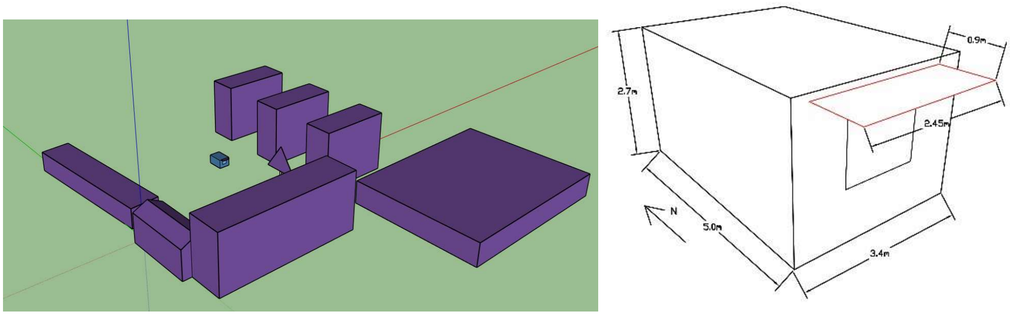

***Figure 2**. A Detail building geometric model with surroundings*

Design variables

Imagine a scene that a designer want to design and optimize the overhang of this case room. Four different design variables are considered and their alternatives are shown in Table 1. These four variables typically express the shapes and aesthetics of fixed shadings. In this study, the variation of reflectance is not considered, since its reflectance of diffuse daylight has little influence on the indoor daylighting environment. The slats used to reflect daylight into ceiling of room to improve daylighting efficiency is called shelf which is modeled by another model called DaylightingDevice:Shelf in EnergyPlus.

Table 1. *Design variables and numbers of design experiments*

Variables	Alternatives	Unit	Numbers of design experiments
∇_{angle}	-30, -15, 0 , 15, 30	[deg]	5
∇_{Length}	-1.0, -0.8, -0.4, 0, 0.4, 0.8, 1.0	[m]	7
∇_{Depth}	-0.5, -0.3, 0, 0.3, 0.5, 0.7, 0.9	[m]	7
$\nabla_{\text{Distance above window}}$	-0.25, 0, 0.25, 0.5, 0.75	[m]	5
Total number of experiments			1225

Multi-objective functions and optimization algorithm

Typically, conflicting objectives, such as cost and performance, are used in building performance design optimization. In this case study, two annual climatic-based complement objectives of solar heat gain in summer and UDI are used to evaluate the shapes of overhang and help designers make trade-off decision which known as the Pareto-optimal solutions. Solar heat gain in summer is chosen as one of the two objective functions because more energy is used for cooling than heating in Nanjing. UDI represents concept of time, for example $UDI_{>2000lux}$ of one analyzed area means times of daylight illuminance above 2000lux. So we use room area ratio of area whose $UDI_{100\sim2000lux}$ >=50% to total room area as the other objective function which means the smaller of 1- $UDI_{100\sim2000lux}$ >50%, the better of the design is. A global optimization method of Multi-objective GA (MOGA) which also knows as evolutionary algorithm, is employed in this design and optimization process.

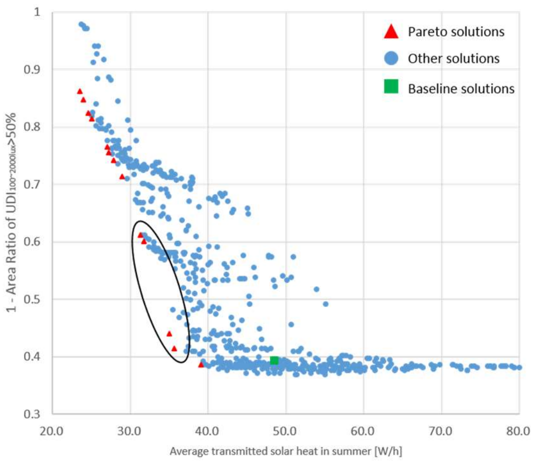

Figure 3. *The Pareto optimal solutions and other solutions of the proposed overhang design strategies*

Results analysis

Since the total number of experiment is small, the stop criteria, such as max_function_evaluations is not set. The optimization processes are repeated 605 times. Figure 3 shows the non-dominated Pareto optimal solutions and other candidate solutions. The results in the ellipse are optimal or near-optimal solutions that have a moderate objective functions that designers may interested in. Figure 3 also shows that there are tens of solutions whose two objective functions better than the baseline design. Table 2 summarizes several Pareto or near-optimal and baseline solutions' design variables and objective functions. Increasing shading slats' length and depth may result to less solar heat gain, but also affects daylighting (Figure 3 Pareto4 VS Pareto5).

***Table 2**. Baseline, several Pareto and near-optimal solutions' optimization results*

Solutions	$\nabla_{Lengt.}$	∇_{Depth}	$\nabla_{\mathrm{Distance}}$	∇_{angle}	F1	F2
Baseline	0.0	0.0	0.0	0.0	48.69	0.3906
Pareto1	1.0	0.7	-0.25	15.0	31.76	0.6000
Pareto2	1.0	0.3	-0.25	0.0	31.36	0.6118
Pareto3	1.0	0.9	-0.25	30.0	35.07	0.4400
Pareto4	0.8	0.9	-0.25	30.0	35.68	0.4141
Pareto5	0.0	0.9	-0.25	30.0	39.14	0.3859
Pareto6	0.4	0.7	-0.25	-15	27.04	0.7647
Near-optimal1	1.0	0.7	0.0	15.0	35.48	0.4824
Near-optimal2	0.8	0.3	0.0	0.0	37.37	0.4729

F1: objective function of solar heat gains, F2 objective function of UDI.

CONCLUSION

To design a high performance building, designers need the help of powerful techniques and tools to conducted performance design and optimization in the early design stage. With the optimization technological advances in the early 21st century, designers theoretically can and will do it. However, building optimization problems are solved from the engineering point of view other than from designers. That explains why designers are reluctant to use these optimization tools. In this research, we proposed a designer-friendly simulation-based optimization scheme. This paper summarized the fixed shading design problem with a view of designers and enumerated several evaluation criteria, among which visual comfort is not easy to judge with existing method in EnergyPlus and more advanced glare calculation method need to be added. Cumulative solar heat gain and UDI are both annual climatic based criteria which are more preferable than criteria at specific time point.

In the case study, the proposed method and tool truly helps find out designs that have better solar heat and daylighting performance. The Pareto and the near optimal solutions are candidate designs from which designers decide the best solutions. The design optimization tool has advantage of calculation, but humans good at thinking and making decision. In the future much more calculation function should be added in the proposed method and tool, for example cost analysis.

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