Multi-objective optimization of building facade design strategies

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ABSTRACT

Achieving optimal solutions to design high-performance building façade is a challenging task at the early design stage, since a huge number of facade design variables have to be implemented in a comprehensive framework. The life cycle cost (LCC) and indoor comfort are essential optimization constraints but often conflict with each other. In this study, an efficient, transparent and time-saving optimization method is implemented to improve a two-floor office building's façade in the severe cold climate of China. Facade design variables such as insulation, window-to-wall ratio (WWR), and glazing types are explored. Useful daylight illuminance (UDI) and life cycle cost (LCC) were applied as design objectives. A stochastic population-based and multi-dimensional optimization technique of Strength Pareto Evolutionary Algorithm-II (SPEA-II) is utilized for searching the optimization space. The lighting simulation program Radiance and energy simulation program EnergyPlus are integrated with this optimization tool to compute the optimal solutions. The optimization results validate the potential to maintain low LCC and achieve high UDI value.

KEYWORDS

Multi-objective optimization; UDI; Life cycle cost; Façade design strategy

INTRODUCTION

Energy efficiency, cost optimality, and indoor daylight performance are essential considerations for office building facade design at the early design stage. However, building facade design variables conflict on these design objectives, thus, improving the design variables to minimize or maximize one of these objectives will have a

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negative impact on at least one of the others. Recently, multi-objective optimizations are widely implemented to evaluate the trade-offs between different design objectives.

Simulation-based optimization approaches for building shape (Jin and Jeong 2014), insulation level (Tuhus-Dubrow and Krarti 2010) and other building facade design features are widely implemented to achieve appropriate design solutions. Hasan et al. implemented an LCC optimization of a typical Finnish house construction in accordance with the Finnish National Building Code C3 of 2003 (Hasan et al. 2008). Asadi provided a multi-objective optimization scheme to reduce the energy demand, operation cost and thermal comfort of a residential building retrofit (Asadi et al. 2012) Fesanghary developed a multi-objective optimization model based on harmony search algorithm (HS) to minimize the LCC and carbon dioxide equivalent (CO_2-eq) emissions of a typical single-family house (Fesanghary et al. 2012). While all these studies mentioned above only considered energy efficiency and thermal performance as the optimization objectives, Futrell presented a bi-objective optimization method using Hooke Jeeves and Particle Swarm Optimization algorithm (PSO/HJ) to optimize the daylight and thermal performance of a single-zone classroom design (Futrell et al. 2015). A Pareto frontier (Abbass et al. 2001) was approximated to help evaluate trade-offs between thermal and daylight objectives for each orientation.

In this study, a multi-objective optimization which is based on the Strength Pareto Evolutionary Algorithm-II (SPEA-II) (Zitzler et al. 2001) is investigated for a two-floor office building in the severe cold climate of China, with the design objectives of UDI and LCC. The optimization results can help the architects and engineers to find appropriate strategies which would be most useful and profitable under specific conditions.

MULTI-OBJECTIVE MODEL AND METHODOLOGY

Multi-objective optimization problem

A multi-objective optimization (MOO) based on the SPEA-II is implemented to achieve appropriate facade design strategies. The optimization objectives are the minimum of LCC and the maximum of UDI. The facade design variables include window width, window height, glazing types, and external wall insulation thickness. The width and height of windows will create different WWRs for facades. Therefore, four façade design variables are defined concerning the alternative choices regarding:

- v_1 - window width;
- v_2 - window height;
- v_3 - glazing types;
- v_4 - external wall insulation thickness.

Objective function calculation procedures

Annual total energy demand. Generally the energy sources of an office building are used for space heating, cooling, artificial lighting and domestic hot water systems. In this specific model, domestic hot water is not considered. A climate-based calculation methodology is implemented here to estimate the heating, cooling and artificial lighting energy demand. Therefore, the general procedure for estimating the annual energy demand Q_{total} can be generalized and expressed as:

$$Q_{total} = Q_{heating} + Q_{cooling} + Q_{lighitng} \quad (1)$$

where,
Q_{total} – total energy demand;
$Q_{heating}$ – energy demand for space heating [kWh/year (Btu/ft^2·h·°F/year)];
$Q_{cooling}$ – energy demand for space cooling [kWh/year (Btu/ft^2·h·°F/year)];
$Q_{lighitng}$ – energy demand for artificial lighting [kWh/year (Btu/ft^2·h·°F/year)].

The annual artificial lighting energy demand is obtained by applying the average hourly energy demand and the total usage hours during the working schedule, which depends on the total daylight illuminance. The grid of points on the work plane height were uniformly distributed on a 1.0m × 1.0m (3.3ft × 3.3ft) grid, which created a 14 by 9 grid in the office room for lighting simulation (Fig.1). The target illuminance value E_{min} of the office room is 500 lux, which determines the total hours of artificial lighting use T. The artificial lighting power density P is 11.74W/m^2 (0.0010Btu/s·ft^2). Therefore, the artificial lighting energy consumption can be explained expressed in the following equation:

$$Q_{lighitng} = P \times T \times A \quad (2)$$

where
P is the installed lighting power, the unit is [W/m^2 (Btu/s·ft^2)],
T is the total hours of artificial lighting use in a year, the unit is [h],
A is the floor area, the unit is [m^2 (ft^2)]

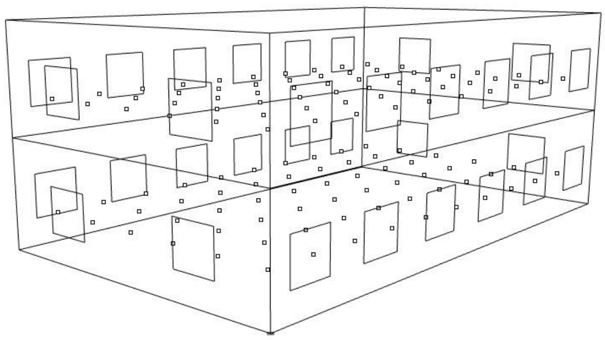


Fig 1. *3D geometry and sensor points of the building.*

Cost of investment. The overall investment cost for the building facade is calculated by adding the costs corresponding to each action as follows:

$$I_{initial} = A_{EWAL} \times C_{EWAL} + A_{WIN} \times C_{WIN} \quad (3)$$

$A_{WIN} = v_1 \times v_1 \times n$ (4)

where,

$I_{initial}$– initial investment;

C_{WIN}– cost in [$\$/m^2(\$/ft^2)$] for window type;

C_{EWAL}– cost in [$\$/m^2$ ($\$/ft^2$)] for external wall type;

A_{EWAL} –total external wall area exclude window [m^2 (ft^2)];

A_{WIN}– total window area [m^2 (ft^2)];

n – total window number;

Net present value of the life-cycle cost. Net present value of life-cycle cost is the evaluation criteria used in this study, which is calculated by following equation:

$$LCC = I_{initial} + t \times (Q_{total} \times P) \quad (5)$$

where $I_{initial}$ is the initial investment of the building construction strategy, P is the present energy cost for electricity (year 2016), and t is the calculated life-time period for the LCC. The maintenance cost and residual cost are not included in this study.

Visual comfort assessment in buildings. Useful daylight illuminance (UDI) is used in this study to evaluate the daylight performance based on both daylight availability and visual comfort in the studied space. Useful daylight illuminance (UDI) is defined as the percentage of time if an entire year when indoor horizontal illuminance at a given point that satisfies a selected daylight range (Nabil and Mardaljevic 2006). A lower and an upper bound of illuminance values are proposed in order to split the analyzed schedule into three bins, representing the percentage of time with (i) an oversupply illuminance level ($UDI_{Overlit}$), (ii) an appropriate illuminance level ($UDI_{Preferred}$) and (iii) an insufficient illuminance level ($UDI_{Underlit}$).

$$UDI = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1] \quad (6)$$

$$UDI_{Overlit} \quad \text{with } wf_i = \begin{cases} 1 \text{ if } E_{Daylight} > E_{Upper\ limit} \\ 0 \text{ if } E_{Daylight} \leq E_{Upper\ limit} \end{cases}$$

$$UDI_{Preferred} \text{ with } wf_i = \begin{cases} 1\ if\ E_{Lower\ limt} \leq E_{Daylight} \leq E_{Upper\ limit} \\ 0\ if\ E_{Daylight} < E_{Lower\ limit} \vee E_{Daylight} > E_{Upper\ limit} \end{cases}$$

$$UDI_{Underlit} \quad \text{with } wf_i = \begin{cases} 1 \text{ if } E_{Daylight} < E_{Lower\ limit} \\ 0 \text{ if } E_{Daylight} \geq E_{Lower\ limit} \end{cases}$$

In Equation (6), the lower bound and upper bound of UDI are set to 100 lux and 2000 lux respectively. The objective is to maximize the percentage of office area which can meet the $UDI_{Preferred}$ value. In this study, the objective for daylight performance is to maximize the percent values of floor area that meets the UDI criteria at least 50% of the time.

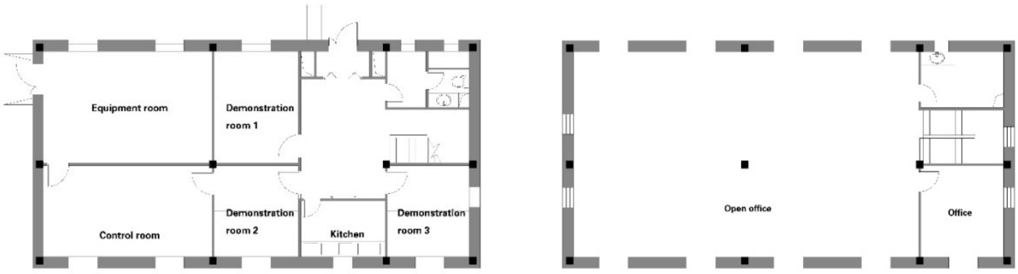
Solution techniques

As discussed above, the design variables, objective functions and constraints developed, lead to the formulation of the multi-objective problem:

$$\min Z_1(x) = LCC(x) \quad (7)$$
$$\max Z_2(x) = UDI(x) \quad (8)$$

CASE STUDY

The aim of this section is to illustrate how to implement the described optimization method in the façade design process. The case study is an on-campus office building used for technology demonstrations. The latitude and longitude of the city are 41.8°N, 123.4°E, respectively. The average elevation of the urban area is 45m (148ft) above the sea level. The average temperatures are below -10°C (14°F) in January and below 25°C (77°F) in July. By the local code GB50176-93 - Thermal design code for civil building, the site is characterized as a severe cold climate. The building has two floors above ground with a 300m^2 (3229ft^2) rectangular floor plan (Fig.2). The initial purpose of this building is to develop an office building for the College of Environmental Engineering, which has the functions of demonstrating and presenting the passive and active building technologies, as well as office and laboratory uses.



Ground Floor | Second Floor

***Fig 2.** Schematic plan of ground floor and second floor of case study.*

According to the local code DB21/T1899-2011 - Design standard for 65% energy saving of public buildings, mechanical heating and cooling are set to 22°C (71.6°F) and 26°C (78.8°F), respectively. The lighting load is set to 11.74W/m^2 (0.001Btu/s·ft^2) and the internal heat gain per unit of floor area is set to 4W/m^2 (0.0004Btu/s·ft^2). The energy resource for heating, cooling and artificial lighting is electricity. A heating efficiency of 0.8 and cooling system coefficient of performance (COP) of 3.0 is used for the annual heating and cooling energy consumption. The setup is shown in Table 1.

***Table 11**. Model Setup*

Parameter	*Value (SI units)*	*Value (IP units)*
Lighting power density	11.74 W/m^2	0.001 Btu/s·ft^2
Equipment power density	4 W/m^2	0.0004 Btu/s·ft^2
Floor U-Value	0.11 W/m^2·K	0.019 Btu/ft^2·h·°F
Ceiling U-Value	0.09 W/m^2·K	0.016 Btu/ft^2·h·°F

Occupancy density	0.1 person/m^2	1 person/ft^2
Heating COP	0.8	0.8
Cooling COP	3.0	3.0
Ventilation rate	0.009 m^3/s - person	0.32 ft^3/s - person
Infiltration rate	0.25 air changes/h	0.25 air changes/h

A list of alternative facade design strategies applied in this study is noted by the authors. Typical design variables including window width (v_1), window height (v_2), glazing types (v_3), and external wall insulation materials thickness (v_4) are considered to improve UDI, as well as to reduce the LCC. According to these design variables, there are totally 18088 (14 × 19 × 6 × 8) possible solutions for this optimization problem, the full enumeration technique is not implementable in this case since the daylight and thermal simulation process is extremely time-consuming. Tables 2~4 represent the facade design variables.

***Table* 22**. *Window Size (v_1, v_2)*

Type	*Range (m)*	*Uniform Step (0.05m)*	*Range (ft)*	*Uniform Step (0.16ft)*
Width	From 0.6 to 1.25	13	From 1.97 to 4.10	13
Height	From 1.2 to 2.1	18	From 3.94 to 6.89	18

***Table* 33**. *Glazing Types (v_3)*

N	*Type*	*U-value (W/m^{2}K)*	*U-value (Btu/ft^2·h ·°F)*	*SHGC*	*Tvis*	*Cost (\$/m^2)*	*Cost (\$/ft^2)*
G1	Single Clear-6mm thick	6	1.05	0.7	0.88	20.8	1.93
G2	Single Tint-6mm+12A+6mm	2.7	0.47	0.62	0.8	27.7	2.57
G3	Double Clear Low-E-6mm+12A+6mm	1.8	0.31	0.6	0.65	123.3	11.46
G4	Double Low-E Argon-6mm+12A+6mm	1.5	0.26	0.34	0.65	184.9	17.18
G5	Triple Tint Air - 3mm/13mm	1.1	0.19	0.31	0.47	231.1	21.48
G6	Triple Tint Low-E Argon - 3mm/13mm	0.7	0.12	0.24	0.30	277.3	25.77

***Table* 44**. *External Wall Insulation (v_4)*

N	*Thickness (m)*	*Thickness (ft)*	*U-value (W/m^{2}K)*	*U-value (Btu/ft^2·h·°F)*	*Cost (\$/m^2)*	*Cost(\$/ft^2)*
W1	0.05	0.16	0.369	0.064	14.9	1.38
W2	0.10	0.33	0.269	0.047	18.0	1.67
W3	0.15	0.49	0.211	0.037	21.1	1.96
W4	0.20	0.66	0.174	0.031	24.3	2.26
W5	0.25	0.82	0.152	0.027	27.4	2.55
W6	0.30	0.98	0.128	0.025	30.5	2.83
W7	0.35	1.15	0.114	0.020	33.6	3.12
W8	0.40	1.31	0.102	0.018	36.8	3.42

RESULTS AND DISCUSSION

To improve the optimization efficiency of SPEA-II, 20 populations are created for each generation. All the values of design variables are discrete. The dimension boundaries of window width and height are divided by a constant step from 0.05 m (0.16 ft) to 14 and 19 options, respectively. The insulation boundary of wall construction is divided by a constant step 0.05 m (0.16 ft). The number of glazing types is 6. Finally, the total window dimension, glazing type and wall insulation are achieved by only 400 simulation runs during the optimization process.

Several observations of daylight performance and LCC of this case study can be made from the Pareto frontier. The parameters are listed in Table 5. Three points on the Pareto frontier, designated a, b, and c, which represent the point for minimum LCC, a middle point and the point for maximum LCC, are pointed out.

The minimum LCC and best daylight performance is a combination of appropriate window size, window height, glazing type and wall insulation variables that simultaneously provide the appropriate amount of daylight to the office space year-round and provide solar heat gain during the cooling and heating seasons, and minimize the initial cost by reducing the percentage of window area on the external wall. At point a, the window width is 0.6m (1.97ft), the window height is 1.3m (4.27ft), the glazing is G2 and the external wall insulation is W7, the percentage of floor area of 50% UDI reaches the maximum, which is 78%, and the LCC reaches the minimum, which is the 126500.9 $. The result of point b shows that the window width is 0.65m (2.13ft), the window height is 1.6m (5.25ft), the glazing is G2 and the external wall insulation is W6, the percentage of floor area of 50% UDI is 64%, and the LCC is 128847.5$. When the LCC reaches the maximum, at point c, which is 152009.9$, the percentage of floor area of 50% UDI reaches the minimum, which is 42%, the window width is 1.15m (3.77ft), the window height is 1.6m (5.25ft), the glazing is G3 and the external wall insulation is W5. The results show that in this climate, trying to achieve a maximum window size will generally lead to poor daylight performance due to glare problem, while costing more money on the investment of façade construction.

Table 5. *Optimization results*

Solution	*LCC($)*	*UDI*	W_{Width} *(m)*	W_{Height} *(m)*	*Glazing*	*EWAL*
a	126500.9	78%	0.6	1.3	2	7
b	128847.5	64%	0.65	1.6	2	6
c	152009.9	42%	1.15	1.6	3	5

CONCLUSION

A multi-objective optimization based on SPEA-II was implemented in this study, to achieve the optimal solutions for LCC and UDI of a two-story office building façade design. Daylight and thermal performance may conflict since large window openings admit more daylight and provide weak resistance to heat conduction and solar radiation. At the same time, LCC and UDI can sometimes conflict since the window size will have a variable impact on the UDI and the initial investment. However, since the analyzed schedule of UDI is divided into three bins, it is difficult to predict if the LCC and UDI will conflict with each other or not. Therefore, the multi-objective optimization method is efficient and robustness to achieve appropriate design solutions and help designers to make decisions at the early design stage.

The results show that, when the LCC is the minimum, which is 126500.9$, the percentage of floor area of 50% UDI reaches the maximum 78%. Therefore, the LCC and the daylight performance do not conflict with each other in this case. However, the UDI value doesn't depend on the WWR but depends on the shape of the windows, which is described as window width and height in this study. When the UDI reaches the maximum value of 78% at point a, the window width is 0.6m (1.97 ft) and window height is 1.3m (4.27 ft).

The optimization results provide the appropriate facade design variables which can achieve both good economic and daylight performance. It also demonstrates that the method of SPEA-II can largely reduce the simulation time in a multi-objective optimization problem.

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