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Design optimization of office building envelope configurations for energy conservation

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HIGHLIGHTS

- Building Envelope Energy Load (*ENVLOAD*) is essential for green building design.
- Office Building Envelope design Model (OBEM) was developed based on *ENVLOAD*.
- OBEM provides envelope configurations for architects' reference.
- Tabu search links OBEM to optimize an office building envelope configuration.
- Optimized design reduces construction cost under energy conservation regulations.

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ABSTRACT

Designing envelope configurations of office building with the low construction cost and energy consumption is a discrete optimization problem. The configuration is currently determined merely on architects' experiences resulting in an inefficient expense or by building energy performance simulation which is time-intensive and involves complex processes. Based on an efficient regression equation to substitute complex energy simulators, this study developed an Office Building envelope Energy performance and configuration Model (OBEM) to provide envelope configurations, including construction material, sunshade type, sunshade length, window number, and window length and width for architects' reference. Also, Tabu search, which is effective in solving discrete optimization problems, was integrated with OBEM into an Optimal OBEM decision support system (OPOBEM). The OPOBEM was applied to a real office building construction for optimizing its envelope configuration at minimum construction budget under the energy conservation regulations of green buildings. The result shows that the optimized installation of sunshade type efficiently reduces solar heat gain according to the high variation of the sunshade coefficient, thus achieves the goal of energy conservation and reduces the envelope costs. Compared with architects' manual estimation, the optimized envelope design realizes nearly 41% budget savings, thus demonstrating the feasibility of the proposed OPOBEM.

1. Introduction

Constructing green buildings with nearly zero-energy is a major objective in energy policies worldwide [1]. Building envelope features considerably affect the energy efficiency of buildings, indoor environmental quality and the thermal comfort for human [2–4]; thus, the effective evaluation of the thermal performance of building envelopes is crucial in the reduction of air-conditioning energy consumption [5]. Specifically, precise design of building envelope can significantly help improve energy efficiencies of building [6]. Several building envelope energy efficiency standards, such as Overall Thermal Transfer Value (OTTV) equation and Perimeter Annual Load (PLA), were proposed and revised to apply to different buildings in different countries according to climate type, analysis period (such as summer or whole year), or building type [5,7,8]. The OTTV is doubtful to be selected as an effective index in Taiwan, where cooling load predominates [9]. The PLA proposed by Japan government is defined as annual thermal load of perimeter spaces within 5 m of exterior wall [10]. Comprehensive building thermal

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Nomenclature

Ac	annual cooling air-conditioning hours, h/yr
A_i	areas of the window glass in the air-conditioned zone in ith sector, m^2
A'_i	areas of the window glass in the non-air-conditioned zone in ith sector, m^2
AFp	total air-conditioning floor areas in building perimeter zones, m^2
B_i	wall areas in the air-conditioned zone in the ith sector, m^2
B'_i	wall areas in the non-air-conditioned zone in ith sector, m^2
C_i	glass curtain areas in the air-conditioned zone in ith sector, m^2
C'_i	glass curtain areas in the non-air-conditioned zone in ith sector, m^2
C_g	unit costs of window glass, NTD/m
C_w	unit costs of wall, NTD/m
C_u	unit costs of glass curtain, NTD/m
C_r	unit costs of roof, NTD/m
C_s	unit costs of sunshade board, NTD/m
D_i	roof areas in the air-conditioned zone in ith sector
D'_i	roof areas in the non-air-conditioned zone in ith sector, m^2
DH	annual degree-hours based on monthly average temperature (298 K), K h/yr
dr	sunshade depth rate, %
E_i	sunshade board areas in the ith sector, m^2
FW_i	total width of building in ith sector, m
G	annual indoor heat gain, W h/m^2 yr
IH_k	isolation-hours on k orientation of building, W h/m^2 yr
K_i	sunshade coefficient of window in the ith sector
L_i	heat loss coefficient of building envelope in the ith sector, W/m^2 K
Mk_i	insolation gain coefficient on k orientation of the building envelope in the ith sector, dimensionless
N_i	window number of building in the ith sector
OR	calculated window opening rates of the building, %
OR_o	original design window opening rates of the building, %
R_l	requested lower limit of *ENVLOAD*, kW h/m^2 yr
R_u	requested upper limit of *ENVLOAD*, kW h/m^2 yr
SL_i	sunshade board length in the ith sector, m
Ti	sectors number of the building envelope, dimensionless
Tu	increment in the average room temperature, K
U_l	thermal conductivity of the wall, W/m^2 K
U_m	thermal conductivity of the glass curtain, W/m^2 K
U_n	thermal conductivity of the roof, W/m^2 K
$Vaira_i$	air-conditioned zone areas in the ith sector, m^2
$Vunaira_i$	non-air-conditioned zone areas in the in the ith sector, m^2
W_i	window width in the ith sector, m
WL_i	window length in the ith sector, m

Greek letters

η_i	solar transmittance of glass, dimensionless

Acronyms

OBEM	Office Building envelope Energy performance and configuration Model
OPOBEM	Optimal Office Building envelope Energy performance and configuration Model
TRNSYS	TRaNient SYstems Simulation program
ENVLOAD	annual building Envelope energy Load, kW h/m^2 yr

performance simulation models, such as whole building energy simulation program and Transient Systems Simulation Program (TRNSYS), were used to facilitate estimating building energy performance [11–13]. However, the operation of such simulation programs is time-intensive and involves complex processes [14,15]. To simplify the complex processes of estimating the building energy performance and apply quickly to practical problems, Magnier and Haghighat used TRNSYS to create a building energy database for training artificial neural networks (ANNs) and combined a simulation-based ANNs with a multiobjective algorithm for optimizing building design [16]. Similarly, some studies presented simple regression expression for predicting annual building energy performance based on the simulation results of commercial building energy programs [17–19]. Chou and Chang extended the regression concept to predict a peak cooling load of building [20]. In Taiwan, a building Envelope Energy Load (*ENVLOAD*) regression equation was developed by modifying the PLA with local climatic data to estimate building envelope energy performance [9,18,21–23]. The *ENVLOAD* representing the total annual cooling and heating load in perimeter of buildings per unit floor area [9,18] was established based on case studies of hundreds of buildings with different climatic contexts in tropical and subtropical monsoon regions [23]. A low *ENVLOAD* value indicates low building envelope energy demand and high energy conservation [24] so to be a design index for green buildings [21,25,26]. However, the *ENVLOAD* is currently calculated by architects' manual determination based on the architectural blueprint that limits its applicability. In addition, architects often design building envelopes for energy conservation on the basis of their experience, but such subjective approaches may not yield the optimal design features [27] and may result in a high construction budget. An optimized building envelope is required to achieve a high energy performance of the building in green building design [28]. Studies used optimization approaches to aid architects in selecting the optimal building envelope features [29,30]. For example, Fesanghary et al. minimized energy consumption by altering building envelope materials, including insulation type, roofing, and window type, size, and glazing [31]. In other words, efficient building envelope performance assessment techniques and energy consumption indices are essential in green building design.

In building design optimization, architects must sometimes assign integer or discrete values to building design variables [32,33]. Heuristic algorithms, such as genetic algorithm and Tabu search (TS), were demonstrated to be a useful optimizer to solve continuous and discrete optimization problems [34–37]. Ha et al. used TS to manage the power consumption in a home automation system by determining the starting time of some services [38]. Meanwhile, TS was also found more effective than other optimizers for resolving mixed-integer nonlinear programming [39]. Few researches utilized TS to optimize a building design, and none of studies reported on optimizing office building envelope features in Taiwan. In addition, office buildings are considered as the major growing source of energy consumption in urban area [5]. Hence, this study is to develop an Optimal Office Building envelope Energy performance and configuration Model (OPOBEM). First, Office Building envelope Energy estimation and configuration Model (OBEM) was built based on the *ENVLOAD* equation. The OBEM provides office building *ENVLOAD* and useful office building envelope