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Building Envelope Retrofit Optimization Considering Performance Degradation

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ABSTRACT

The envelope system is responsible for about 40% of the total energy consumption in a general building. Therefore, building envelope retrofit is an effective method to reduce the energy demand of buildings. In this paper, an optimization model for building envelope retrofit considering performance degradation is proposed to help decision makers to obtain an accurate optimal retrofit plan with a given budget, aiming at maximizing the energy savings and economic benefits. Specifically, the model determines the optimal retrofit options for the windows, walls, roof and a roof-top PV system from their alternatives. Considering that facilities will inevitably age over time, the performance degradation of the envelope components after retrofit is built into the model to ensure the accuracy of the optimal retrofit plan. A case study is carried out to demonstrate the feasibility and effectiveness of the proposed optimization model.

Keywords: building envelope retrofit, roof-top PV system, multi-objective optimization, performance degradation, energy efficiency

NONMENCLATURE

Abbreviations

CDM	Clean development mechanism
PCM	Phase change materials
PV	Photovoltaic
WWR	Window to wall ratios

Symbols

β	Total investment ($)
φ_1	A constant related to building envelope
φ_1	A constant related to PV panels
η_s	Average efficiency of converting solar energy to electricity
η_m	Efficiency of the m-th solar panel alternative
λ_j	Thermal conductivity of the j-th alternative of wall insulation materials (W/m°C)
λ_k	Thermal conductivity of the k-th alternative of roof insulation materials (W/m°C)
t_j	Thickness of the j-th alternative of wall insulation materials (m)
t_k	Thickness of the k-th alternative of roof insulation materials (m)
A_m^{pv}	Area of one solar panel of the m-th alternative (m^2)
A_{flr}	Area of floor (m^2)
A_{wal}	Area of walls (m^2)
A_{win}	Area of windows (m^2)
A_{rof}	Area of roof (m^2)
A_{rofeff}	Effective area on the roof for the PV system installation (m^2)
C_{dd}	Cooling degree days (CDD) in year t
Cf_1	Absolute value of the cumulative cash flow at the end of the N-th month
Cf_2	Absolute value of the cumulative cash flow at the end of the (N+1)-th month
C_i^{win}	Cost of the i-th window alternative ($/m^2)
C_j^{wal}	Cost of the j-th wall ($/m^2)
C_k^{rof}	Cost of the k-th roof ($/m^2)
C_m^{pv}	Cost of one solar panel of the m-th alternative ($)
$E_{cool}(t)$	Total energy consumption in cooling seasons in year t
$E_{heat}(t)$	Total energy consumption in heating seasons in year t
$E_i(t)$	Internal heat gain in year t
$E_{lc}(t)$	Latent heat gain in year t
$E_{lh}(t)$	Latent heat gain in year t
$E_{sc}(t)$	Infiltration and ventilation heat gain in year t
$E_{sh}(t)$	Infiltration and ventilation heat loss in year

	t
E_{pre}	Total energy consumption before retrofit
$E_{pv}(t)$	Electrical energy generated by the PV panels in year t
ES	Energy savings in the project period
$E_{sl}(t)$	Solar heat gain in year t
$E_{tc}(t)$	Transfer heat gain in year t
$E_{th}(t)$	Transfer heat loss in year t
$E_{tot}(t)$	Total energy consumption in year t
H_{dd}	Heating degree days (HDD) in year t
$HSPF$	Heating seasonal performance factor
$I_{pv}(t)$	Solar irradiation on the PV power supply system during year t (kWh/m^2)
$I_{win}(t)$	Solar irradiance of the window in year t
N	Last month with negative cumulative discounted cash flow
$N_{pv}(t)$	Number of PV panels working in year t
$R_{win}(t)$	Degradation of windows in year t
$R_{wal}(t)$	Degradation of wall insulation materials in year t
$R_{rof}(t)$	Degradation of roof insulation materials in year t
$SEER$	Seasonal energy efficiency ratio
$SHGC(t)$	Solar heat gain coefficient
Tp	Payback period (months)
$T_s(t)$	Solar radiation time in year t
U_i	U-value of the i-th window alternative
U_w	U-value of walls before retrofit (kWh/m^2)
U_r	U-value of roof before retrofit (kWh/m^2)
U_{win}	U-value of windows after retrofit (kWh/m^2)
U_{wal}	U-value of walls after retrofit (kWh/m^2)
U_{rof}	U-value of roof after retrofit (kWh/m^2)
U_{flr}	U-value of floor (kWh/m^2)
x_i^{win}	State of the i-th alternative of windows
x_j^{wal}	State of the j-th alternative of walls
x_k^{rof}	State of the k-th alternative of roof
x_m^{pv}	State of the m-th alternative of PV panels

1. INTRODUCTION

The energy consumed by the building sector accounts for a large proportion of the total energy consumption in the world, which is about 38.5% in the United States, 40% in the European Union, and 37% in China [1-2]. Therefore, building energy conservation has attracted much attention from the industry and researchers [3-5]. One of the most effective methods to reduce the energy demand of the building sector is to retrofit existing buildings with high-efficient facilities [6-8]. As the energy exchange between buildings and the external environment is through building envelope systems, about 40% energy consumption of a general building is caused by its envelope [9]. Hence, building envelope retrofit can effectively increase the energy efficiency of buildings.

In the literature, lot of work has been done on building envelope retrofit, aiming at improving the energy efficiency of buildings. Lago et al. analyzed the thermal performance of double glazing [10]. Zhang et al. considered to add a film made of metal nanoparticles to the windows to improve the energy performance of buildings [11]. Saafi et al. analyzed the energy and cost efficiency of integrating PCM on building envelopes [12]. Milic et al. evaluated cost-optimal building envelope renovation strategies for 12 typical historic buildings in Sweden using LCC optimization and 12-38% energy savings could be obtained [13]. Azari et al. optimized the parameters, such as insulation materials, south and north WWR and so on, to obtain a best envelope design combination for low-rise office buildings to balance the energy use and environmental impact [14]. Acar et al. investigated building envelope parameters, such as external wall materials and thermal mass, etc., to enhance the energy and economic performance of buildings in heating and cooling dominant climates [15].

In our previous study [16], an optimization model for building envelope retrofit problems was also proposed to maximize the energy and economic benefits of buildings. These studies mentioned above increased the energy or economic performance of buildings effectively. However, the performance degradation of building envelope components is not taken into account. As we know, all building facilities will age over time inevitably, resulting in performance degradation or even non-functioning. Therefore, it is necessary to consider performance degradation in building energy retrofit problems so that the obtained results are more accurate and practical. In the literature, some work related to performance degradation has been done. For instance, Fan et al. modeled a roof-top PV system with its performance degradation and a maintenance plan for energy sustainability in a building retrofit optimization problem [17]. Ye et al. introduced a lamp population decay model into CDM lighting projects, the purpose of which was to determine an optimal sampling plan with a minimum metering cost [18]. Aisyah et al. combined an artificial intelligence method with ISO 15686 Buildings to predict the degradation and service life of building components [19]. Eleftheriadis et al. reviewed the impact of the deterioration of building components on the whole building performance, and the results showed that the impact ranged from 20% to 30% over 20 years [20]. However, few studies were found to consider facility performance degradation in building envelope retrofit problems.

Therefore, an optimization model for building envelope retrofit planning considering performance degradation is proposed to obtain an accurate retrofit plan optimally with the purpose of maximizing the energy savings and minimizing the payback period. Specifically, the windows are to be retrofitted with high-efficient alternatives, the walls and roof are considered to be installed with insulation systems, and a roof-top solar panel system is considered to be installed. The multi-objective problem is solved with the weighted sum method, thereby, decision makers are able to get a desired retrofit plan according to their preferences on different objectives by tuning the weighting factors.

The remaining part of this paper is organized as follows. Section 2 presents an optimization model for building envelope retrofit considering performance degradation. The results and analysis of a case study is provided in Section 3. After that, conclusions are drawn in Section 4.

2. OPTIMIZATION MODEL

In this section, an optimization model for building envelope retrofit considering performance degradation is built. The purpose of this study is to maximize energy savings and economic benefits. Therefore, the energy and economic models of the building envelope retrofit project need to be established first.

2.1 Energy model

The energy performance of a target building can be expressed as the difference between the energy consumed by the building and that generated by the roof-top PV system installed. The energy consumption and generation of the building are calculated as follows [21-23].

It should be noted that the energy savings of the building envelope retrofit project are calculated by the difference in the energy consumed by the building before and after retrofit. As a result, the energy consumption of some parts in the energy model, which is not affected by the retrofit, will be eliminated directly. Therefore, the energy consumption formulations of these parts are not listed in this section due to space limit.

2.1.1 Heating energy consumption

The energy consumption of a general building in heating seasons consists of transmission heat loss and infiltration and ventilation heat loss.

The transmission heat loss can be calculated by the following equation. The floor of the building is not considered to be retrofitted.

$$E_{th}(t) = H_{dd}\left(\frac{A_{win}U_{win}}{R_{win}(t)} + \frac{A_{wal}U_{wal}}{R_{wal}(t)} + \frac{A_{rof}U_{rof}}{R_{rof}(t)} + A_{flr}U_{flr}\right) \quad (1)$$

in which

$$U_{win} = \sum_{i=1}^{I} x_i^{win} U_i$$
$$U_{wal} = \sum_{j=1}^{J} x_j^{wal} \frac{U_w \lambda_j}{U_w d_j + \lambda_j}, \quad (2)$$
$$U_{rof} = \sum_{k=1}^{K} x_k^{rof} \frac{U_r \lambda_k}{U_r d_k + \lambda_k}$$

The performance degradation of the retrofitted windows, walls and roof can be described as follows [24]

$$R(t) = e^{-(\frac{t}{\varphi_1})^{0.5}} \quad (3)$$

The model of infiltration and ventilation heat loss is not presented here as it is not affected by the retrofit. Therefore, the energy consumption of the heating load in year t can be calculated by

$$E_{heat}(t) = \frac{E_{th}(t) + E_{sh}(t) + E_{lh}(t)}{HSPF} \quad (4)$$

2.1.2 Cooling energy consumption

The energy consumption of a general building in cooling seasons consists of transmission heat gain, infiltration and ventilation heat gain, solar heat gain, and internal heat gain.

The transmission heat gain can be calculated by

$$E_{tc}(t) = C_{dd}\left(\frac{A_{win}U_{win}}{R_{win}(t)} + \frac{A_{wal}U_{wal}}{R_{wal}(t)} + \frac{A_{rof}U_{rof}}{R_{rof}(t)} + A_{flr}U_{flr}\right) \quad (5)$$

The solar heat gain can be calculated by

$$E_{sl} = A_{win} I_{win}(t) SHGC(t) T_s(t) \quad (6)$$

in which the calculation of $SHGC(t)$ is related to the retrofit option of windows.

The models of the infiltration and ventilation heat gain and internal heat gain are not present here as they are not affected by the retrofit. Then the energy consumption of the cooling load in year t can be calculated by

$$E_{cool}(t)=\frac{E_{tc}(t)+E_{lc}(t)+E_{sc}(t)+E_{sl}(t)+E_i}{SEER} \tag{7}$$

2.1.3 PV power generation

The roof-top PV system can provide electricity for buildings to reduce energy consumption. The energy generated by the PV system can be calculated by

$$E_{pv}(t)=I_{pv}(t)\eta_s\sum_{m=1}^{M}x_m^{pv}\eta_m A_m^{pv}N_{pv}R_{pv}(t) \tag{8}$$

in which $R_{pv}(t)$ can be calculated by [25]

$$R_{pv}(t)=e^{-(\frac{t}{\varphi_2})^3} \tag{9}$$

2.1.4 Total energy consumption

According to the sections from 2.1.1 to 2.1.3, the total energy consumption of the building can be calculated by

$$E_{tot}(t)=E_{cool}(t)+E_{heat}(t)-E_{pv}(t) \tag{10}$$

2.2 Economic model

The total cost of the entire renovation process can be calculated by

$$\begin{aligned}Cost &= A_{win}\sum_{i=1}^{I}x_i^{win}C_i^{win}+A_{wal}\sum_{j=1}^{J}x_j^{wal}C_j^{wal}\\ &+A_{rof}\sum_{k=1}^{K}x_i^{rof}C_i^{rof}+N_{pv}\sum_{m=1}^{M}x_m^{pv}C_m^{pv}\end{aligned} \tag{11}$$

The energy savings obtained in year t can be calculated by

$$ES=\sum_{t=1}^{T}(E_{pre}-E_{tot}(t)) \tag{12}$$

Payback period can be calculated by [26]

$$Tp=N+\frac{Cf_1}{Cf_2} \tag{13}$$

2.3 Optimization model

2.3.1 Decision variable

Assume that there are I, J, K, M alternatives for retrofitting the windows, walls, roof and installing the PV system, respectively. Let

$$x_{win}=\left[x_1^{win},x_2^{win},\cdots,x_I^{win}\right]$$
$$x_{wal}=\left[x_1^{wal},x_2^{wal},\cdots,x_J^{wal}\right]$$
$$x_{rof}=\left[x_1^{rof},x_2^{rof},\cdots,x_K^{rof}\right]$$
$$x_{pv}=\left[x_1^{pv},x_2^{pv},\cdots,x_M^{pv}\right]$$

Then the decision variable for this optimization problem can be expressed by

$$X=\left[x_{win},x_{wal},x_{rof},x_{pv},N_{pv}\right]$$

2.3.2 Objective function

The objectives of the building retrofit optimization problem are to maximize the energy savings and minimize the payback period. With the weighted sum method, the multi-objective optimization problem can be transferred into a single-objective one as follows [27-29].

$$F=-\omega_1\overline{ES}+\omega_2\overline{Tp} \tag{14}$$

in which ω_1 and ω_2 are the weights of the energy savings and payback period, respectively, and ω_1, ω_2 need to satisfy $\{\omega_1+\omega_2=1\}$

2.3.3 Constraints

There are three constraints in this optimization problem. The first constraint is a limited budget, which can be expressed as:

$$Cost\le\beta \tag{15}$$

The second one is the boundary limits on the decision variables, which can be expressed as

$$\begin{cases}\sum_{i=1}^{I}x_i^{win}\in\{0,1\},i=1,2,\cdots,I\\ \sum_{j=1}^{J}x_j^{wal}\in\{0,1\},j=1,2,\cdots,J\\ \sum_{k=1}^{K}x_k^{rof}\in\{0,1\},k=1,2,\cdots,K\\ \sum_{m=1}^{M}x_m^{pv}\in\{0,1\},m=1,2,\cdots,M\end{cases} \tag{16}$$

The third one is that the total area of the PV system installed on the roof must be less than the effective area of the roof, which can be expressed as

$$N_{pv}\sum_{m=1}^{M}X_m^{pv}A_m^{pv}\le A_{rofeff} \tag{17}$$

3. RESULT AND ANALYSIS

To demonstrate the feasibility and effectiveness of the proposed optimization model, a two-story office building is taken as a case study. In this case, the windows are considered to be retrofit with new ones, the walls and roof are considered to be installed with insulation materials and a roof-top PV system is considered to be installed. There are 5, 13, 10 and 7 alternatives for retrofitting the windows, walls, roof and installing the PV system, respectively. The detailed information of these alternatives refers to the paper [26] and is not listed here due to space limit. The effective area for the PV system installation is 200 m^2, and the building retrofit project period is 24 years.

The optimization problem is solved and the optimal results with different budgets are presented in Table 1.

Table 1: Optimal retrofit plans under different budgets with weighting factors $\omega_1 = 0.7$ and $\omega_2 = 0.3$

option	1	2	3	4
budget($)	20000	40000	60000	80000
window	3	3	3	3
wall	0	10	8	7
roof	2	6	6	4
pv	4	4	4	5
N_{pv}	2	21	39	79
ES(kWh)	248406	362175	475546	619515
Tp(month)	144	156	168	168
ESrate	8.60%	12.50%	16.40%	21.40%
AllCost($)	19715	39819	59625	79617

In the table, the parameters, "window, wall, roof, pv, N_{pv}", indicate the optimal retrofit options and the number of installed solar panels, respectively. "ES, Tp, ESrate, Cost" means the energy savings, payback period, percentage of energy savings compared to the building's energy consumption before retrofit and the retrofit cost, respectively. For instance, the numbers "3, 7, 4, 5, 79" in the fifth column of Table 1 mean that the windows, walls and roof are retrofitted with the third, seventh and fourth alternatives, respectively, and the PV system is installed with 79 solar panels of the fifth alternative. The other numbers in the column mean that 21.4% energy can be saved and the cost of $79617 can be paid back in 168 months with a budget of $80000. The "0" in the second column means that the walls are not considered to be retrofitted.

It can be seen from Table 1 that the energy savings and payback period keep increasing with growing budgets. With a budget of $20000, the windows and roof are firstly considered to be retrofitted. While the walls are not considered to be retrofitted and only two solar panels are built into the PV system. The reasons for this are that the wall retrofit cost is high due to the large area of the walls and the solar panels are expensive. When the budget increases from $20000 to $40000, the walls are considered to be retrofitted with the tenth alternative. The roof retrofit option changes from the second one to the sixth one and the number of installed solar panels increases from 2 to 21. This is because the performance of the sixth roof alternative is better than that of the second one and the productivity of the PV system is high. When the budget increases from $40000 to $60000, the retrofit option of walls changes to the eighth one while the retrofit option of the roof remains unchanged. And the number of installed solar panels increases to 39. This means that the retrofit priority is given to the roof and PV system firstly when the budget is enough. When there are still remaining investments, a better option is chosen for wall retrofit. When the budget increases to $80000, a relatively cheaper solar panel option is chosen for the PV system installation and the number increases to 79. The retrofit options of the walls and roof are changed to the seventh and fourth alternatives, respectively.

It can be found that the payback period of this case is large. For instance, the payback period of the forth retrofit plan is 168 months. Two reasons can explain this phenomenon. Firstly, the payback period of building envelope retrofit is known to have a longer payback period than other facility retrofit, such as lightings, HVAC systems, etc. Secondly, the performance degradation of the retrofitted building components is considered during the whole building retrofit project. Therefore, it can be concluded that performance degradation of building components influences the retrofit planning and needs to be considered in building retrofit projects.

4. CONCLUSION

In this study, an energy-efficiency optimization model for building envelope retrofit considering performance degradation is proposed, aiming at maximizing the energy savings and minimizing the payback period with a given budget. The windows, walls, roof of the building are considered to be retrofitted and a PV system is considered to be installed on the roof. The performance degradation of the above components after retrofit is built into the optimization model to ensure the accuracy of obtained optimal retrofit plans. The multi-objective optimization problem is solved with the weighted sum method, which allows decision makers to get an optimal solution according to their preferences on different objectives. A case study is carried out and the results demonstrate the feasibility and effectiveness of the proposed optimization model.

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