

installation is 200 m², 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 fourth 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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