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MULTI-OBJECTIVE OPTIMIZATION FOR BUILDING ENERGY RETROFITTING CONSIDERING USER SATISFACTION

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ABSTRACT

This paper proposes an improved multi-objective optimization model for building energy retrofitting. Apart from the extensively investigated objectives: minimizing the overall energy consumption and reducing the life cycle cost, another objective is involved: the overall user satisfaction during operation. The newly introduced objective reflects the fact that upon the deterioration of appliances, the user satisfaction decreases accordingly, and this must be reversed via facility maintenance. A multi-objective optimization model with all three objectives is established to support the building energy retrofitting decision making. A recently proposed many-objective optimization algorithm, NSGA-III, is employed as the numerical solver. A simulation test is conducted and the relationship between objectives are investigated.

Keywords: energy efficiency retrofits, Multi-objective optimization, user's satisfaction

1. INTRODUCTION

The building energy retrofitting has drawn enormous attention over the past decades. A number of relevant studies can be referred on the retrofitting optimization [1,2,4]. The existing studies mainly focused on two objectives: minimizing energy consumption (EC), and minimizing retrofitting costs.

The main purpose of this study is to introduce a new objective in addition to the conventional ones: user satisfaction (US). Different with the satisfaction on thermal comfort or building functionality, the term US hereby refers to a unique concept: the ability of the retrofitted appliances to provide sustainable service level against performance deterioration upon operation. The electrical appliances in public buildings are investigated at the current stage. Due to the lack of quantitative studies, a Sigmoid function is employed to estimate the performance deterioration. Such a function was employed to describe the population decay of lighting facilities [3].

In addition, the Life cycle cost (LCC) is incorporated into the optimization. As a result, a global cost (GC) is hereby introduced, which consists of two parts: the initial investment and the annual maintenance cost of the electrical devices. The GC is employed as the performance indicator to minimize retrofitting costs.

Given the three different objectives with promising conflicts, the conventional optimization algorithm might be limited in solving such a complicated problem. A many objective optimization algorithm, NSGA-III, is hereby employed as our numerical solver. The newly proposed algorithm guarantees the diversity of the obtained solutions, so as to find a satisfying result.

The remainder of the paper consists of three sections. Section 2 introduces the modelling of the multi-objective optimization and the numerical solver. Section 3 gives case study and simulation to verify the proposed approach. Section 4 draws conclusions.

2. MODELING

Table 1 Design variables of energy efficiency retrofits

Intervention	Alternetives	i_{th}	N_j
Lighting system	Energy Saving Lamp	x_2	N_1
	Light Emitting Diode	x_3	
Air Conditioning system	Inverter Air Conditioner	x_5	N_2
Elevator Brake system	Feedback Brake Elevator	x_7	N_3
Renewable energy system	Photovoltaic	x_8	N_4

2.1 Decision variables

The decision variables indicate how interventions are implemented. In this case, four intervention categories are taken into considerations: Lighting system, Air Conditioning system, Elevator brake system and Renew-able energy system, as listed in Table 1. Each category corresponds to a number of electrical appliances to be retrofitted. N_1 to N_4 denote such appliance numbers respectively. x_2, x_3, x_5, x_7, x_8 are the decision variables that denote the number of retrofitted appliances, corresponding to a specific technology. It allows that a part of the appliances remain not retrofitted. x_1, x_4, x_6 are employed to denote the number of unretrofitted appliances, as they also contribute to the performance calculation. Variables x_1 to x_8 follow Eq. (1):

$$\begin{cases} x_1 = N_1 - (x_2 + x_3) \\ x_4 = N_2 - x_5 \\ x_6 = N_3 - x_7 \\ x_8 \leq N_4 \end{cases}, \quad (1)$$

2.2 Objective functions

Minimizing the post-retrofit energy consumption (*EC*) over the evaluation cycle T, is our first objective. EC is calculated via stacking the average energy consump-tion of different appliances and integrate them over the full cycle of evaluation. Such an average energy consumption is derived from the estimated average power and working hours. When taking into account the renewable energy, e.g., the PV system in this case, the appliance consumptions supported by the renewable energy is deducted from EC. The specific calculation formula is shown in Eq. (2).

$$EC = \sum_{t=0}^{T} \sum_{i=1}^{7} x_i * w_i(t) * \overline{h}_i(t)$$

$$- \sum_{t=0}^{T} x_8 * w_8(t) * E_i * (1 - L_c) * \overline{h}_8, \quad (2)$$

where $w_i(t)$ is the power of the i_{th} type of electrical device upon time t, $\overline{h}_i$ is the average daily working hours. $w_8(t)$ is the output of PV system. E_i and is L_c are the inverter conversion efficiency and the percentage of loss for solar curtailment.

The second objective is minimizing global cost. The GC is formulated as Eq. (3).

$$GC = IC + \sum_{t=0}^{T} \sum_{i=1}^{8} MR_i(t) * R_{d_t}(t), \quad (3)$$

Where IC denotes the initial investment. It is calculated as Eq. (4):

$$IC = \sum_{i=0}^{8} IC_i * x_i, \quad (4)$$

Where IC_i is the unit cost of implementing the i_{th} appliance. For items that are not retrofitted, $IC_i = 0$. MR_i is the maintenance cost of the i_{th} electrical device upon time t. The maintenance takes place periodically, and $MR_i = 0$ if t is not the time of maintenance. R_{d_t} denotes the discount rate of future cash flow. It is calculated by the Eq. (5). [2]

$$R_{d_t}(t) = \left(\frac{1}{1 + \frac{R_r}{100}} \right)^t, \quad (5)$$

where R_r is the real interest rate. R_r is usually calculated by the inflation rate (R_{int}) and the interest rate (R_i), according to Eq. (6)

$$R_r = \frac{Ri_{int}}{1 + \frac{R_i}{100}}. \quad (6)$$

Maximizing user satisfaction over the evaluation cycle is the last objective. It is estimated via Eq. (7):

$$US = \sum_{t=0}^{T} \sum_{i=1}^{8} \omega_i * \int_0^{L_t} s_i(t) dt, \quad (7)$$

where ω_i is the weighting factor that indicates the user dependence on different electrical appliances. L_t is the period time of maintenance or replacement for

Table 2 Detailed parameters of the renovation plan

Intervention	Alternetives	i_{th}	$\overline{h}_i$	Lifespan (year)	L_t (year)	Unit price/Repair fees(￥)	ω_i	power
Lighting system	Incandescent Lamp	x_1	12h/day	1	1	0/2	0.15	80W
	Energy Saving Lamp	x_2		3	2	10/10	0.15	14W
	Light Emitting Diode	x_3		10	5	60/60	0.20	7W
Air Conditioning system	Fixed Frequency Air Conditioner	x_4	6h/day	10	2	0/120	0.20	1.5p(3500w)
	Inverter Air Conditioner	x_5		10	2	3500/150	0.30	1.5P(3500w)
Elevator Brake system	Resistance Brake Elevator	x_6	-	-	-	0/-	-	40KW·h/day
	Feedback Brake Elevator	x_7		-	-	5000/-	-	22KW·h/day
Renewable energy system	Photovoltaic	x_8	5h/day	-	-	600/-	-	120W/plate

the ith appliance. $S_i(t)$ denotes a sigmoid function, which estimates the performance deterioration of the i_{th} appliance. The formulation of $S_i(t)$ is given in Eq. (8):

$$S_i(t) = \frac{1}{c_i + e^{b_i * t - L_i}} \text{ ,} \quad (8)$$

where c_i, b_i and L_i are the parameters of the function, and L_i is the lifespan of i_{th} appliance. The identification of parameters can be referred to [4].

In addition, MR is directly affected by L_t, the maintenance period. In case that the appliances are replaced or repaired at a higher frequency, a higher US can be achieved, at the cost of higher MR, and vice versa.

$$Min\{EC, GC, -US\}$$
$$s.t. \begin{cases} IC \le IC_0 \\ US \ge US_0 \\ x_1 + x_2 + x_3 = N_1 \\ x_4 + x_5 = N_2 \\ x_6 + x_7 = N_3 \\ x_8 \le N_4 \\ x_i \ge 0, x_i \in N^+ (i = 1,2 \cdots 8) \end{cases} \quad (9)$$

2.3 Numerical solver

The multi-objective optimization algorithm, NSGA-III[5], is hereby employed as the numerical solver. It is an improved algorithm based on the framework of NSGA-II[6]. In NSGA-II, nondomination levels are used to sort the population quickly, then, crowding distance is used to ensure population diversity. NSGA-II has good performance with less than three objectives. However, when the objectives are equal to or more than three, crowding distance lacks the ability to characterize the population diversity. Therefore, the NSGA-III uses a predefined set of reference points to guarantee the diversity in obtained solutions [5].

The constraints of actual optimization problem are often not box constraints. As is shown in Eq. (9), there are several linear and non-negative constraints, as well as integer constraints. Jain and Deb proposed a processing method of constraints in [7], and uses binary coding to solve the integer programming problem. Such an approach is hereby employed.

The idea of simulated annealing is used in the gene mutation in the algorithm, which makes the initial mutation degree of the operation larger, and the closer to the end mutation, the smaller the mutation.

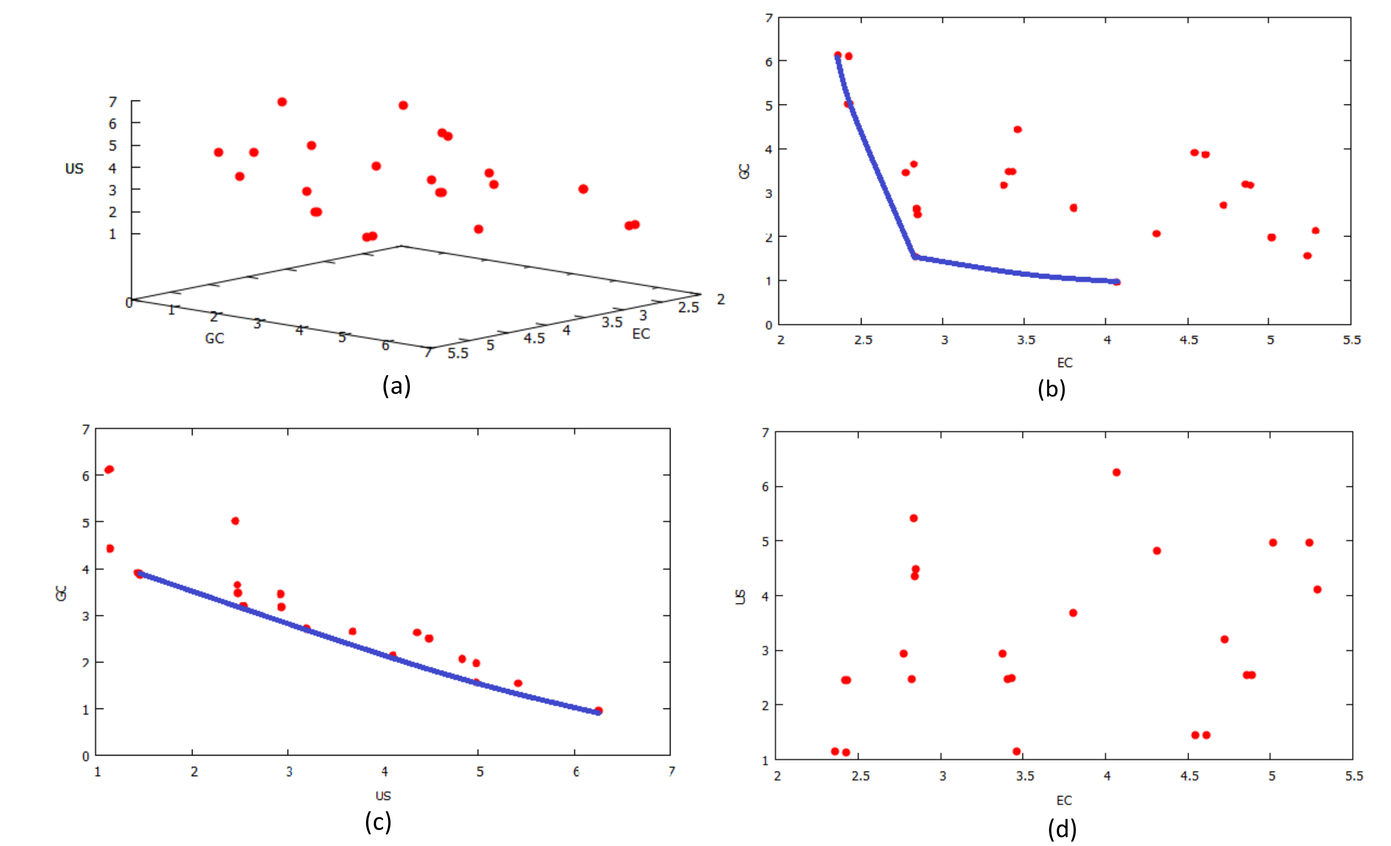

Fig 1 Simulation results

(a) Three-dimensional visualization (EC, GC, US), (b) Two-dimensional projection (EC and GC), (c) Two-dimensional projection (GC and US), (d) Two-dimensional projection (EC and US). And all results have been modulo processed for the convenience of display.

3. SIMULATION AND ANALYSIS

3.1 Case study

The research object referenced in this paper is the south 1st building of the East Campus of Huazhong University of Science and Technology in Hubei. It has about a hundred rooms, each with 10 lights and an air conditioner, and three elevators are included in the entire building. There is a space of 100 square meters on the top of the building for PV panels.

As shown in Table 2, the detailed variables involved are listed. The values of lifespan and power in Table 2 are from the nameplate of the electrical devices. $\overline{h}_i$, L_t and Unit price/Repair fees are the average from market research. Given that the rated lifespans of the elevator feedback brake device and PV plates are generally longer than the entire life cycle of the appliance, as well as the evaluation cycle, the maintenance of the device is excluded in the case study. Consequently, the user satisfaction of the two interventions is considered to be constant instead of Sigmoid function during operation in the case study. Finally, considering the good performance of LEDs and the hot weather in southern Chinese cities, the weighting factors of LEDs and ACs are relatively high.

The involved interest rate is cited from [8] and the inflation rate from [9].

3.2 Simulation results and discussion

The simulation results are shown in Fig 1, where (a), (b), (c), (d) are the three-dimensional Pareto solution and its two-dimensional projection in the other three planes.

The scales of the figures are modulo processed for the sake of clearer demonstration. The EC scale is 3650 kwh per interval (number of days in 10 years). The GC scale is 1000 yuan per interval. The demonstrated US is processed to be $10 - US$. In this way, the axis scales are adjusted to be at the same level.

The blue line in (b) and (c) are the projections of the Pareto front. There is no obvious projection of Pareto front in (d), which is consistent with the designed objective, where there is no direct connection or conflict between US and EC.

4. CONCLUSIONS

This paper proposes a multi-objective optimization model, where three objectives are involved. A user satis-faction that describes the sustainability of the retrofitted appliance service level is newly proposed in the optimization problem. A recently proposed many-objective optimization algorithm, NSGA-III, is employed to solve the problem. A case study, where a university educational building is retrofitted, is adopted to test and verify the proposed approach.

The simulation results illustrate a Pareto front of the three-objective optimization. From the results, a decision maker could choose the implementation plan of the building energy retrofitting, with the balance among the aforementioned objectives. The trade-off among objectives, especially between the GC and US, are clearly demonstrated.

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