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MULTI-OBJECTIVE OPTIMIZATION OF EQUITY, CONSUMPTION AND THERMAL COMFORT OF HVAC SYSTEM BASED ON INDOOR TRAJECTORIES

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ABSTRACT: Heating, Ventilating and Air Conditioning system is leading a trend of optimization for occupant-relevant built environment energy performance. In this study, we present a new indicator, comfort equity and optimization technique to improve this occupant-related system energy performance comprehensively with the utilization of indoor trajectory data. Multi-objective particle swarm optimization algorithm is used to conduct optimal temperature setpoint solutions to optimize thermal comfort, comfort equity and energy efficiency.
Keywords: Heating, Ventilating and Air Conditioning system, energy performance, equity, thermal comfort, multi-objective optimization

NONMENCLATURE

Abbreviations	
HVAC	Heating, Ventilating and Air Conditioning
SDG	Sustainable Development Goals
MOPSO	Multi-Objective Particle Swarm Optimization
EEI	Energy Efficiency Indicators
TRNSYS	Transient System Simulation Program
PMV	Predicted Mean Vote
PPD	Predicted Proportion of Dissatisfaction
Symbols	
t_a	Air Temperature
t_r	Radiant Temperature
r_h	Relative Humidity
v_{ar}	Air Speed
M	Metabolic Rate
I_{cl}	Clothing Insultation

1. INTRODUCTION

1.1 Background

In rapid-developing modern society with popularized consciousness of sustainability and social development mode, the energy consumption of buildings demands intelligent technology for high energy efficiency and occupants' satisfaction simultaneously. The energy usage of building components takes over nearly 30% of the global final energy consumption, estimated to reach 60% by 2060. Among all the sectors of energy end-use in indoor environment, HVAC system takes the largest proportion, nearly 46.4%[1], owing to the reinforcement of building services, comfort levels and the global average indoor time as 87%[2]. It leads to a focus on its occupancy-based energy performance, initially including the comfort need, an acknowledged demand-driven objective, and comfort equity, which evaluates the allocation of energy accessibility, occupying essential social significance. Moreover, considering the integrating concerns on generalized equality in SDGs, the balance among occupants on thermal comfort is accordingly deserving discussion. However, unrestrained enhancement on the above factors realized by exceeded energy consumption of HVAC system represents low energy efficiency. Hence, the appropriate goal of indoor HVAC system energy should be reaching multi-objective optimization of equity, thermal comfort and energy efficiency simultaneously, which could contribute management, design and construction industries as well, which technically and humanely make practicable applications. For improving the factuality and accuracy, indoor trajectory data, which has been broadly used in building emergency evacuation[3], is also of high practicability for indoor energy optimization.

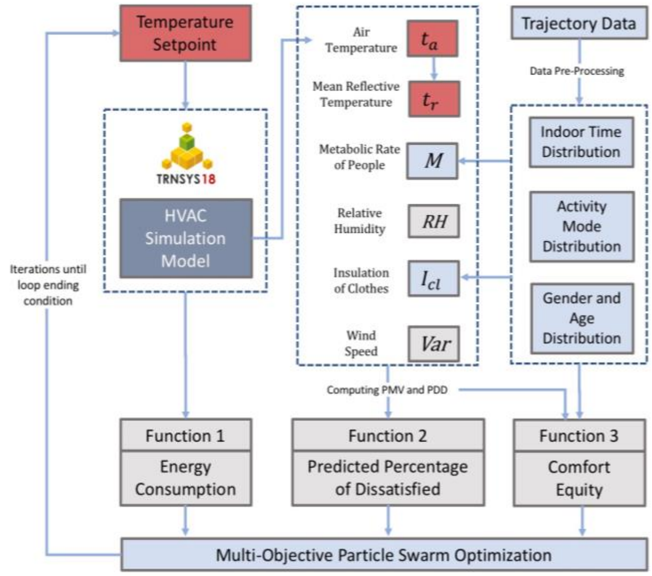

Fig 1 Proposed Framework of Optimization

The optimization framework of this study is shown in Fig.1. In this study, we propose a sequence of solutions and designing strategies that achieve optimization of equity, thermal comfort and energy efficiency of HVAC system with accurate utilization of indoor multi-occupant trajectories. The analysis will take the diversity of scenarios under uncertainty of trajectories into consideration. Related to multi-objective optimization, this occupancy-based study will abide to horizonal equity principle and mainly deploy MOPSO algorithm.

2. COMPONENTS DESCRIPTION AND METHODOLOGY

2.1 Overview

The optimization framework of this study is briefly shown in Fig.1 and would be further detailed. The first phase is pre-processing of utilized trajectory data for arguments in targeted fitness functions, including gender and age distribution, activity mode and time relativity distribution, enhancing the universality of this study by occupancy-based analysis. In parallel, three significant criterions mentioned in the last section for HVAC system energy performance should be respectively computed with input decision variables and other arguments to establish fitness functions, which would be a core part for optimizing. And the core methodology is MOPSO, which is a loop structure, we set iteration times and ending condition for it to output Pareto optimal set, which contains the tuning results of the decision variable.

2.2 Decision Variables and Fitness Functions

The decision variables represent the main effective factors set considered during the operation to optimize the energy performance of HVAC systems. Specifically, one variable is appointed in this study, temperature setpoint in heating mode and setpoints in heating and cooling mode, which is assumed continuous to enrich the granularity. Initialization is mainly setting the variable value intervals, which are optimizing ones based on HVAC setpoint standards and previous related works.

For HVAC energy consumption measurement, TRNSYS is utilized, which is a simulation package has been used for more than 25 years for HVAC analysis. In succession, we aggregate the simulation results in monthly energy consumption, expressed in MWh.

The evaluation of occupants' thermal comfort would be mainly assessed by PMV and PPD[4], which are two acknowledged criterions for thermal comfort, proposed by P.O.Fanger in 1960s. PMV as an indicator is calculated from a particular combination of t_a, t_r, r_h, v_{ar}, M, I_{cl}, including the variables and data for this study, ranging from -3 (too cold) to +3 (too hot), whereas PPD is expressed as percentage that is easier for quantification. In this study, the air and radiant temperature are decision variables; the metabolic rate and the clothing insulation are from the trajectory data; the relative humidity and wind speed will be set by measurements. With the above parameters, PMV (1) and PPD (2) could be given by:

$$PMV = f\left(t_a,\ t_r, r_h,\ v_{ar}, M, I_{cl}\ \right) \tag{1}$$

$$PPD = 100 - 95 \times \exp(0.03353 \times PMV^4 - 0.2179 \times PMV^2) \tag{2}$$

Correspondingly, the measurement for main criterion of this study, energy equity, will be implemented by Gini Coefficient. We broaden its previous application in economics to present domestic wealth inequality. It is defined mathematically based on the Lorenz curve, plotting the proportion of the total energy usage of the population that is cumulatively consumed by the bottom x of the population in this study. If X_i is the comfort degree of person i, where there are n persons; X_j is the corresponding value on the line at 45 degrees, representing the perfect equality of thermal comfort, then the Gini coefficient G is given by (3):

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|x_i - x_j\right|}{2\sum_{i=1}^{n}\sum_{j=1}^{n}x_j} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|x_i - x_j\right|}{2n\sum_{i=1}^{n}\sum_{j=1}^{n}x_i} \tag{3}$$

2.3 Multi-Objective Particle Swarm Optimization Algorithm

The MOPSO algorithm[5] we utilize in this study extends the heuristic PSO, which was proposed by C.A. Coello in 2002. PSO is an algorithm inspired on the choreography of a bird flock, which can be seen as a distributed behavioral algorithm that performs multidimensional search. The approach of MOPSO with evolutionary algorithms makes evident the notion that using a Pareto ranking scheme utilizes global attraction mechanisms combined with a historical archive of previously found nondominated vectors, motivating convergence towards globally nondominated solutions.

In the implementation of this framework, we arranged two stopping criteria: (i) when the algorithm reaches 30 iterations and (ii) when the average relative change in the fitness function falls below 1e-6, which is the default tolerance. Besides, we set the interia weight as 0.8 to accelerate the search efficiency for convergence.

3. STUDY CASE

With the purpose of validating the presented methodology using indoor trajectory data to implement occupancy-based multi-objective optimization, it is applied to a high-rise office building in Tokyo. For experimentation, we choose one office floor of this building showed in Fig.2, which contains the working area with storage facilities and leisure, interior transportation facilities in a common area. Specifically, it is officially used by 157 occupants with 163 office desks and 113 seats for cooperative functions, with a gross floor area of about 1497.75 m^2. As for HVAC consumption structure, heating and cooling loads are supposed to be served by gas boiler and water-cooled chillers respectively in this study. The initialized setpoint range will from 15℃ to 21℃ on heating mode, and from 22℃ to 28℃ on cooling mode.

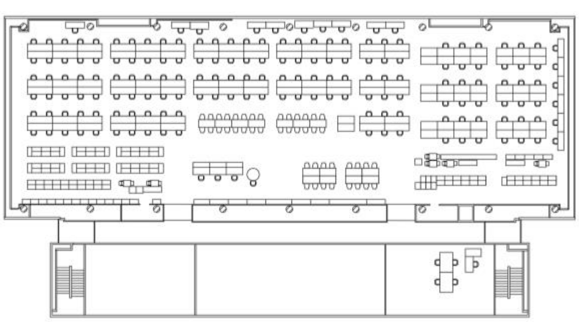

Fig 3 Floor Plan of Case Office Building

For description and analysis strategy of the trajectory data, every piece of data consists of user id, indoor coordinates with the precision of 5 meters, which is taken every 10 minutes from 9 a.m. to 18 a.m. on weekdays for occupancy schedule, which is the working time of this corporation approximately. Aiming at acquiring the corresponding age, gender, independent working time length, cooperative working time length for each user id; for each timestamp with interpolation, the number of occupancies, pre-processing of the data has been implemented.

4. RESULTS AND DISCUSSION

4.1 Optimized Results

We conduct experiments on this study case and the optimization results in this section. Due to the fact that equity, thermal comfort and consumption are in constraints relationship and restricting each other as addressed in MOPSO methodology section, no single optimal solution could be acquired. For each scenario, we could obtain a set of non-dominated solutions, which is Pareto optimal set (Pareto Front).

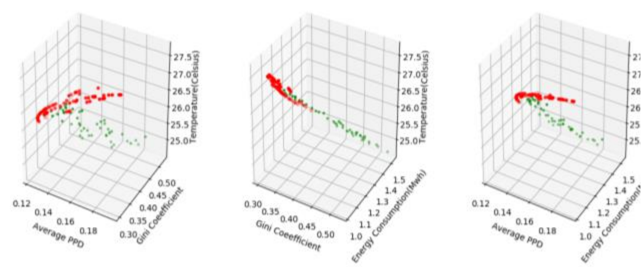

Fig 4 Non-dominated Solutions in Pareto Front

Abiding to the initialization conditions mentioned in the last section, we present the optimization results showing the non-dominated solutions on three criterions. Given that the algorithm is one-dimensional input and three-dimensional output, we separate it into three plots for both scenarios of cooling and heating for it couldn't be presented in one. From Fig.4., we could see the Pareto Front in convergence, constituted by red particles, which are the solutions in Pareto optimal set.

4.2 Discussion

Our work presents substantial evidence for the consideration and proposal of equity criterion is essential and operational for HVAC system temperature setpoint. Under the condition that the occupants and exterior environments remain permanent, we present the distribution of PPD with the input temperature setpoints in cooling mode, in the range from 22℃ to 28℃

neglecting the comfort equity and considering energy consumption, which is on the left of Fig.3. And with the non-dominated solutions in Pareto Front as setpoints input, the distribution is as the right of Fig.5. A prominence with the consideration of comfort equity is that the variance of occupants' PPD decreases by 35.7% with Gini Coefficient of 0.32, which means the balance and fairness of thermal comfort improves in this degree with only 5.6% increasement of average PPD. After proper tuning, with appropriate compromising of average thermal comfort level, the balance of resource allocation rationality improves observably.

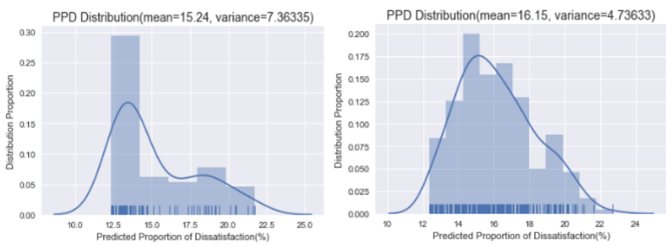

Fig 5 PPD Distribution before and after Equity Optimization

Simultaneously, from Fig.6., the pictures addressed the energy consumption distribution with the same setpoints input as the above figure, and megawatt-hour as unit. Correspondingly, an obvious reduction of average value of about 14.9% and the dispersion degree also shows the potential of equity-relevant multi-objective optimization to realize conservational energy usage and stability of HVAC system.

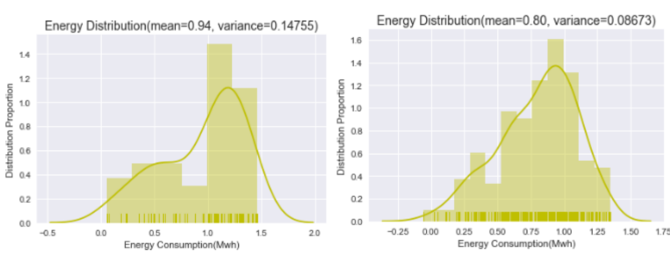

Fig 6 Energy Distribution with and without Equity Optimization

5. CONCLUSION AND FUTURE WORK

In this work, we present a new indicator, comfort equity and optimization technique to improve the occupant-related HVAC system energy performance holistically. Based on indoor trajectory data, we access information more relevant to occupants for metrics calculation. From the results of experimentation, we acquire preliminary conviction that comfort equity and multi-objective optimization with it have the potential to realize low comfort divergence, high average comfort and high energy efficiency simultaneously. Our methods and findings are of practicality and significance to relevant fields. With the scalability of this research, the indicators of HVAC energy performance could be more targeted, sophisticated for distributed energy resource system, which is regarded as a perfect solution for critical environmental issues[6]. Also, corresponding optimized systems could be extended to other interior and exterior conditions, and potential applications of this study are of tremendous expansion value as well.

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