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Room Temperature Dynamic Control and Energy-saving System

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Abstract. According to statistics, the energy consumption of building air conditioning system operation accounts for about 50% of the energy consumption in the building operation phase. Therefore, reducing the energy consumption of building air conditioning systems is of great significance for building energy conservation. The traditional air conditioning system sets a constant temperature during operation and then adopts the PID control method to gradually approach this target value. This method does not take into account dynamic factors such as the building environment, personnel activities, and startup equipment rates, resulting in a large waste of energy consumption and poor comfort. This paper proposes a solution combining the Internet of Things and a heuristic optimization algorithm, in which the Internet of Things is responsible for collecting real-time parameters, and the optimization algorithm is responsible for solving the optimal control strategy, to realize intelligent real-time dynamic adjustment of indoor temperature. By comparing the actual operation results, it can be seen that the control system can reduce power consumption by about 10% and increase user satisfaction by about 8%.

1 Introduction

1.1 Research background

The whole life cycle of building carbon emissions consists of three stages: "Building Materials Production", "Building Construction" and "Building Operation". According to the "China Building Energy Consumption Research Report in 2021" released by the Energy Consumption Statistics Committee of China Building Energy Conservation Association at the end of 2021, in 2019, the total energy consumption of the whole life cycle of buildings in China was 2.233 billion tons of standard coal equivalent (tce), accounting for 45.9% of China's total energy consumption. Among them, the energy consumption of "Building Operation" accounted for 46% of the total energy consumption in the whole life cycle of the building.

Thus, in the building operation stage improving the energy-saving level to reduce carbon emissions has very important significance. In June 2022, the National Development and Reform Commission jointly issued the implementation of urban and rural construction of carbon peak plans. The plan emphasized that it was necessary to improve the energy efficiency of air conditioning, lighting, elevator, and other key energy-using equipment. By 2030, the overall energy efficiency of the existing public building mechanical and electrical systems will be increased by 10%.

Energy consumption of building operation refers to the energy used to provide residents or users with heating, air conditioning, lighting, cooking, domestic hot water, etc., and other energy in residential buildings, office buildings, schools, shopping malls, hotels, transportation hubs, sports, and entertainment facilities. Taking the urban area south of the Yangtze River as an example, in the process of building operation, the energy consumption ratio of lighting systems is about 10%~20%, the energy consumption of air conditioning systems is about 40%~60%, and the energy consumption of other power systems is about 30%~40%. It can be seen that with the increasing improvement of people's quality of life, the proportion of energy consumption of the air conditioning system will be further increased. This paper studies the optimization of building energy consumption, mainly for the energy consumption of the air conditioning system in the building.

In the problem of energy consumption optimization of air conditioning systems, the two most important indicators are power consumption and uncomfortable time. Usually, these two indicators conflict with each other, that is, the reduction of energy consumption will lead to an increase in uncomfortable time. Therefore, energy saving in the operation stage of buildings is a problem of multi-objective optimization. The traditional method is to predict the load at the design stage, determine the design parameters according to the full load prediction value, and then operate according to the set target value during the operation stage, such as setting the temperature of the air conditioner to a constant temperature value. However, this method does not take into account the changes in the environment, the activities of the occupants, etc., which will lead to an increase in building energy consumption and a decrease in comfort. At present, the method of PID control is

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mostly used, although it has the advantages of simple structure and good stability, the building air conditioning is a complex system, with nonlinearity, coupling, lag, multivariable, multi-objective, and other characteristics, it is difficult to achieve the ideal control effect by using the traditional PID control.

1.2 Research status

Ye Tian[1] used Matlab / Simulink software to model the central air conditioning of the whole air system and to simulate the room temperature with the fuzzy PID controller. Junqi Yu[2] proposed an improved parallel particle swarm optimization (IPPSO) algorithm aiming at the optimization problem of cooling water systems. Honglin Xu[3] proposed a genetic algorithm to predict the cooling load of a central air conditioning system in a building. Jiamin Du[4] applied the Grey Wolf optimization (GWO) algorithm to the cold source system of central air conditioning. Dapeng Chen[5] optimized the PID controller parameters and established the mathematical model of the frozen water system by improving the PSO algorithm. Kangji Li[6] compared the advantages and disadvantages of NSGA-II, MOPSO, MODE, MOGA, and other algorithms in terms of execution time, convergence, and optimization effects.

Fabrizio Ascione[7] of Italy proposed a comprehensive framework for multi-objective optimization of building energy design, which performed a multi-stage and multi-objective design optimization, took into account energy consumption, comfort, economic and environmental performance indicators, and optimized in three stages with the overall building-related design variables. Badr Chegari[8] of Morocco studied the optimal solution for energy consumption and comfort in the architectural design stage and compared the performance of three commonly used multi-objective optimization algorithms NSGA-II, MOPSO, and MOGA. N. Delgarm[9] of Iran wrote the MOPSO code in the MATLAB environment and simulated it through the EnergyPlus program. The research pointed out that the level of building energy efficiency could be improved by selecting appropriate building design parameters. Mohammad Amin Ghaderian[10] presented an optimization method based on combining regression models with a multi-objective evolutionary algorithm.

It can be seen from the research situation that the current research work on building energy conservation mainly uses optimization algorithms to simulate and optimize the design of static building models, to predict and improve the energy-saving level of buildings in the design stage. In the actual operation process, there is still a lot of room for research and exploration in the areas such as real-time monitoring of building parameters, dynamic optimization, and adjustment of control strategies.

2 System Design and Implementation

This paper adopts "Internet of Things real-time monitoring + Computer Simulation + Metaheuristic Optimization Algorithm" to solve the building air conditioning system complex energy saving optimization problems, namely tracking the field environment parameters in real-time, dynamically adjusting the control strategy, and choosing the optimal solution between energy consumption and comfort. The advantage of using the simulation means is that it provides a system simulated according to the real environment. The system can analyze and compare the effect and function of the decision according to the presupposition, and make a reasonable optimization choice, to achieve the effect of "an uncertain prophet". The simulation means applied to the decision-making process of energy consumption control of building air conditioning has the advantages of safety, economy, controllable, easy to observe, no destructive and repeated, which can effectively avoid decision-making mistakes and improve the level of macro decision-making planning. The environmental parameters in the building have nonlinear characteristics, and the current mathematical theory can not give the characteristics of feasible solution space. Therefore, on the premise of the limitations of traditional optimization algorithms, the disadvantage is difficult to overcome. The metaheuristic intelligent optimization algorithm does not need to determine the mathematical characteristics of the feasible solution space of the optimization problem in advance but solve the optimization problem by the heuristic method. This paper is based on Niagara + EnergyPlus + MOPSO (multi-objective particle swarm optimization) of the "Internet + virtual simulation + metaheuristic algorithm" solution. Compared with traditional air conditioning systems, this control mode has significant advantages in reducing system delay, reducing energy consumption, and improving user satisfaction. The system is beneficial to reduce the energy consumption of building operation and to improve user comfort, and it has important economic benefits and social significance.

2.1 Main content of the study

The research object of this paper is two laboratories in a teaching building of a university. The construction area of the two laboratories is 96 square meters, the floor height is 4 meters, and there are 50 workstations in each room. One laboratory uses the building energy consumption optimization control system, and the other is the traditional conventional operation mode. Finally, the energy-saving effect of the system is determined in the form of a horizontal comparison.

Since the building air conditioning system is usually designed according to the maximum load demand, and the operation under certain loads will deviate from its optimal state, it is necessary to carry out real-time monitoring during operation and dynamically adjust the operating parameters of each device in the system to maximize the energy efficiency of the system while ensuring the comfort level, this is an important direction for the optimization of energy consumption in air conditioning operation. However, since there is a strong coupling between each factor of building energy consumption, and the influence of some factors is also restricted by seasonal changes, it is usually difficult for decision-makers to establish an accurate mathematical model of building energy efficiency. On the other hand, since the factors affecting energy consumption vary with building types or climates, it is difficult to guarantee the practicability of the built mathematical models. Therefore, the traditional control system still has certain limitations and deficiencies, and it is difficult to achieve the ideal energy-saving optimization effect. This paper uses a dynamic air conditioning control strategy based on a metaheuristic algorithm to optimize energy consumption.

This paper considers the two indicators or objective functions of building energy consumption and user discomfort at the same time and establishes a multi-objective optimization model for the problem. The building energy consumption optimization control system adopts the solution of "Internet of Things + virtual simulation + metaheuristic algorithm". The Internet of Things system adopts the framework of the Internet of Things based on Niagara, which is responsible for collecting real-time data such as on-site temperature and humidity, illuminance, number of people, number of equipment powered on, air velocity, and power consumption, and using infrared signals to control the operation of the air conditioning system in real-time. The virtual simulation system based on EnergyPlus uses, such as the solar heat gain coefficient, the thickness of the external insulation layer of the wall, the solar absorption rate of the external wall, the lighting power density, the heating and cooling set temperature of the air conditioning system, the personnel density, the equipment operating rate, and the indoor temperature and humidity, as the decision variables, and the building energy consumption and discomfort time output by the software are used as the objective function. The metaheuristic algorithm uses Matlab software to call the simulation results of EnergyPlus and run the MOPSO algorithm to obtain the optimal solution of energy consumption and discomfort time.

The paper mainly studies the following aspects:

1) Research on the construction of the Internet of Things air conditioning control system based on the Niagara and Modbus RTU protocols, mainly including the integration of various detectors and actuators, and the development of the Niagara software platform.

2) Research on the construction and operation of building air conditioning simulation systems based on EnergyPlus, Sketch Up, Open Studio, and other software, mainly including building model creation, meteorological modeling, thermal comfort modeling, airflow modeling, HVAC equipment modeling, photovoltaic simulation, etc.

3) Research on the realization of the MOPSO algorithm in the Matlab environment, mainly including the PSO algorithm, Pareto optimal solution set and judgment, interface function of data communication with EnergyPlus, etc.

2.2 Research methods

This paper studies the dynamic operation control strategy of the building air conditioning system and studies how to dynamically adjust the air conditioning operation by using energy-saving optimization algorithms according to the site environment under the premise of ensuring the comfort of the human body in real-time scenarios.

The research work is carried out in the following steps:

1) Deploy various environmental and human sensors, air conditioner controller actuators, IoT gateways, JACE8000 controllers, servers, etc., to build IoT hardware systems;

2) Build an IoT control system on the Niagara Framework 4 platform, integrate, connect, and manage various front-end devices of different brands and collect on-site real-time environmental parameters such as temperature, humidity, illuminance, air velocity, number of people, and number of devices powered on, and send the data to the data server for storing. Figure 1 is the block diagram of the IoT system based on Niagara platform;

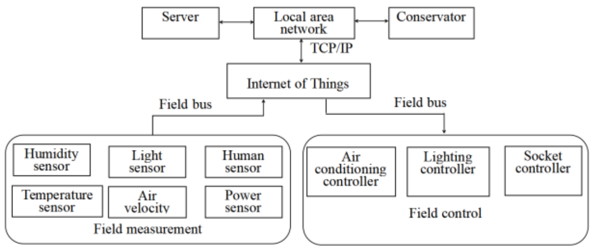

Fig. 1. Block diagram of the IoT system.

3) Use SketchUp software to draw the 3D model of the room, save the model to the IDF format that EnergyPlus can recognize through the plug-in Openstudio, import the model into EnergyPlus, and load the weather file of the area where the building is located through the Weather File function;

4) Add parameters such as location, orientation, walls, windows, shading, air conditioning, and lighting to the model, and read real-time environmental data from the data server, such as indoor temperature, humidity, illuminance, air flow rate, number of people, and number of equipment powered on, and simulate to get building energy consumption and human discomfort hours;

5) Write the coupling function in the Matlab environment, and develop the interface with EnergyPlus based on Visual C++, including variables, interface for calling external programs and feedback data interface, etc;

6) Matlab invokes the MOPSO algorithm, generates new particle positions (parameter values) according to the data fed back by the interface and the variable range set, and iterates until the algorithm meets the termination condition;

7) The Pareto optimal solution saved in the external population is the final result of the algorithm, and the parameters are written into the data server;

8) The Niagara platform reads the optimized parameters, controls the operation of the air conditioner through the controller, and the smart meter records and feeds back the power consumption data and uploads it to the platform. Figure 2 is the flowchart of the simulation and optimization process;

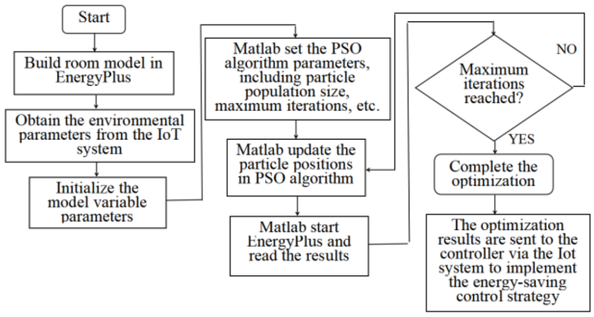

Fig. 2. Simulation and Optimization Process.

9) After a set period of operation, horizontally compare the power consumption of air conditioners in the two laboratories to obtain actual power-saving data, and analyze the user experience, management efficiency, construction and operation costs, safety and environmental protection, etc, and do a comprehensive evaluation of the project.

3 Experimental results

This paper establishes a building model of a university laboratory and uses EnergyPlus software to simulate the air conditioner's energy consumption and discomfort duration based on dynamic temperature control strategies. Figure 3 shows the hardware part of the IoT-based air conditioning energy consumption control system in the room, mainly including IoT controllers, sensors, and gateways.

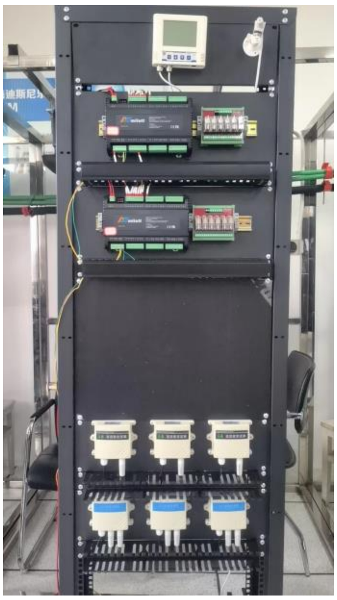

Figure 3. IoT system hardware in the lab.

The building is 96 square meters with a window-to-wall ratio of 0.3. Figure 4 is the room model built in EnergyPlus software.

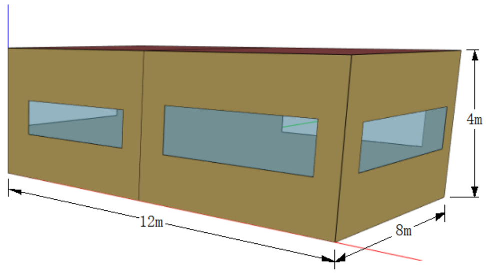

Figure 4. Laboratory building model.

Parameters such as rooms, windows, partition walls, lighting, equipment, personnel, temperature, humidity, and air volume are used as decision variables, and building energy consumption and user discomfort time are used as two objective function values. Table 1 shows the main variables and their values.

Table 1. Variables and their values.

Variable	Unit	Value
Housing direction	angle	0
Length of the window	m	4.8
Height of the window	m	1.4
Heat transfer coefficient of the window	w/(m² *k)	3
Solar heat rate of windows	--	0.5
Thickness of the thermal insulation layer outside the wall	m	0.1
Daily emission absorption rate of the wall	--	0.5
Lighting power density	w/m²	10
Power density of equipment	w/m²	30
Wind speed	m/s	0.5
Personnel density	P/m²	Real-time data from the sensors
Equipment opening rate	%	
Indoor temperature	℃	
Indoor humidity	%RH	
Operating time of the Air Conditioning System	hrs	Operational parameters
Setting temperature of the Air Conditioning System	℃	

When using the particle swarm algorithm, each particle in the search space represents a solution, and the flight direction of all particles is determined by the optimal position of the current particle and the position of the best individual particle in all particles. Therefore, the particles can adaptively adjust the optimization direction according to historical and global information. During repeated iterations, the particles will increasingly converge toward the region of the optimal solution.

$$V_{i,j}(t+1) = wV_{i,j}t + c1r1(pb_{i,j}(t) - x_{i,j}(t)) + c2r2(gb_j(t) - x_{i,j}(t)) \quad (1)$$

$$x_{i,j}(t+1) = x_{i,j}(t) + V_{i,j}(t+1) \quad (2)$$

Where, w is the inertia weight, c1, and c2 are two acceleration coefficients, t is the iteration time, r1 and r2 are two random numbers within [0, 1], gb is the global leader, and pb is the personal leader.

Write and call the PSO algorithm function in Matlab. Part of the code for defining the parameters is as follows:

```
function pop =
PSO_MO_main(p_range,p_discrete,Ini_gene_method,p0_ini_p
ara,NO)
size_pop=100;    % population size
max_gen=200;   % maximum algebra
c1=1.495;         % acceleration factor
c2=1.495;
w_start=0.8;     % initial inertia weight and final inertia weight
w_end=0.2;
km=0.99/size_pop; % population total variation probability
n=length(p_range(1,:)); % variable dimension
pop=struct; %Initialize the output parameters, stored in the
form of structure
V_max=(p_range(2,:)-p_range(1,:))*0.5;    %Define the
maximum and minimum speed
V_min=-V_max;
```

We use a multi-objective decision-making method based on Weighted Sum Model (WSM) to select the best solution from the Pareto optimal set. Assuming n Pareto solutions and 2 optimal design objectives, in the case of minimization, the best solution in the Pareto optimal set satisfies the following expression:

$$R^{*}_{WSM-\text{score}} = \min_{i\in\{1,\ldots,n\}} \sum_{j=1}^{2} w_j F_i^j \qquad (3)$$

Among them, R*WSM-score is the weighted sum score of the best solution on the Pareto front, and the solution with the smallest value is the best; F is the standardized value on the Pareto front; wj is the weight of the j-th optimal design objective. Figure 5 shows the best solution of the Pareto front.

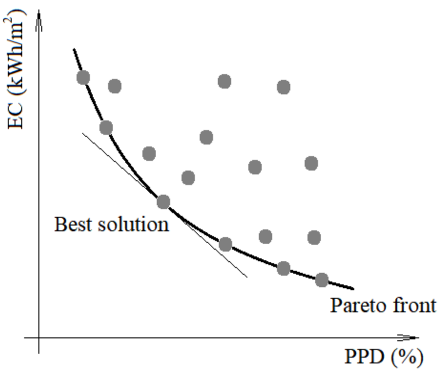

Figure 5. Find the optimal solution on the Pareto front.

Professor Fanger from Denmark proposed the PMV (thermal comfort) equation:

$$\begin{aligned} PWV =& [0.303e^{-0.036M} + 0.028]\{M - W - 3.05\times10^{-3}[5733 \\ & -6.99(M-W) - P_a] - 0.42[(M-W) - 58.15] \\ & -1.7\times10^{-5}M(5867 - P_a) - 0.0014M(34 - t_a) \\ & -3.96\times10^{-8} f_{cl}[(t_{cl}+273)^4 - (t_s+273)^4] \\ & - f_{cl}h_c(t_{cl} - t_a)\} \end{aligned} \qquad (4)$$

This paper makes the following assumptions: take 0.1w/m² for human external work; take 62.5w/m² for metabolic rate; take 0.5m/s for indoor wind speed; take 0.5clo for clothing thermal resistance; and take indoor air temperature for average radiation temperature.

According to the indoor environmental assessment standards ASHRAE 55 and ISO 7730, the comfort limit is expressed by the PMV-PPD index. To meet the thermal comfort requirements of the human body, |PMV| ≤0.5 and PPD≤10% are required. Under this constraint condition, the Pareto optimal solution of discomfort duration and air conditioning energy consumption is solved.

We collect the air conditioning energy consumption and user satisfaction evaluation data of the two laboratories from June 1st to June 30th, 2023, in which the daily air conditioning energy consumption is measured by a dedicated air conditioning meter, the user satisfaction evaluation adopts the statistical method of the questionnaire and takes the percentage of satisfaction. Figure 6 shows the comparison results of the power consumption data, and Figure 7 shows the comparison results of the satisfaction data.

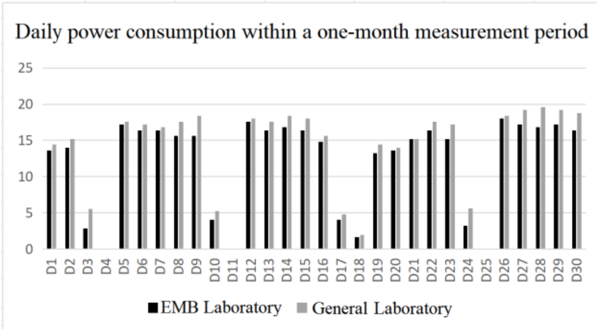

Figure 6. Comparison of power consumption data.

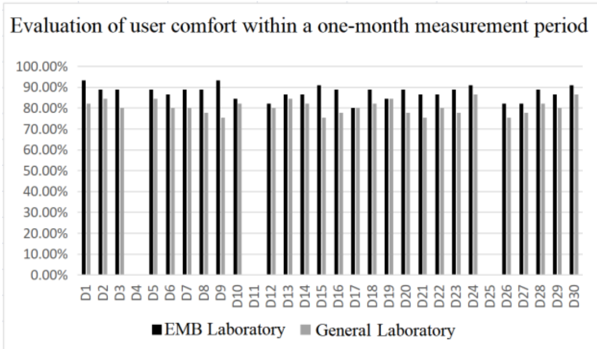

Figure 7. Satisfaction data.

After taking the average value in this measurement period, it can be seen that comfort satisfaction has increased by 8.06%, and the power consumption of the air conditioner has decreased by 10.28%. It can also be observed that the energy-saving effect is more prominent when the number of laboratory students decreases on weekends. This is basically in line with our expectations for the system, that is, when the number of users decreases dynamically, the system can respond in time and adjust the operation strategy to reduce energy consumption.

4 Conclusions

In various large public buildings such as schools, shopping malls, stations, hospitals, and theaters, the air conditioner is usually set to a constant target temperature value, regardless of the change in the external climate environment, the number of people inside, and the occupant's activities. The air conditioner just operates at the set temperature, causing a huge waste of electric energy, and poor comfort. This paper adopts the solution based on Niagara + EnergyPlus + MATLAB + MOPSO, which has significant advantages in reducing system delay, reducing energy consumption, and improving user satisfaction. From the comparison results, it can be seen that energy consumption is reduced by 10%, and satisfaction with comfort increases by 8%.

In future research work, it is also necessary to consider the deployment cost of the system, and the sense of experience of users and managers, and comprehensively evaluate the feasibility of system construction.

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