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Optimization of Intelligent Heating Ventilation Air Conditioning System in Urban Building based on BIM and Artificial Intelligence Technology

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Abstract. The study aims to effectively reduce building energy consumption, improve the utilization efficiency of building resources, reduce the emission of pollutants and greenhouse gases, and protect the ecological environment. A prediction model of heating ventilation air conditioning (HVAC) energy consumption is established by using back propagation neural network (BPNN) and adapted boosting (Adaboost) algorithm. Then, the HVAC system is optimized by building information modeling (BIM). Finally, the effectiveness of the urban intelligent HVAC optimization prediction model based on BIM and artificial intelligence (AI) is further verified by simulation experiments. The research shows that the error of the prediction model is reduced, the accuracy is higher after the Adaboost algorithm is added to BPNN, and the average prediction accuracy is 86%. When the BIM is combined with the prediction model, the HVAC programme of hybrid cooling beam + variable air volume reheating is taken as the optimal programme of HVAC system. The power consumption and gas consumption of the programme are the least, and the CO_2 emission is also the lowest. Programme 1 is compared with programme 3, and the cost is saved by 37% and 15%, respectively. Through the combination of BIM technology and AI technology, the energy consumption of HVAC is effectively reduced, and the resource utilization rate is significantly improved, which can provide theoretical basis for the research of energy-saving equipment.

Keywords: building information modeling, Adaboost-BP algorithm, heating ventilation air conditioning system, energy consumption prediction, simulation.

1. Introduction

As the economy and society develop fast, people's life is becoming more and more stable, and the economic benefits that people pursue at the cost of environment have been retaliated. The high frequency of global extreme climate has seriously threatened people's life safety [1]. With the consumption of resources, there are global energy shortage problems. How to improve the efficiency of energy utilization, reduce resource

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consumption, reduce carbon dioxide emissions, and curb the pace of global greenhouse effect has become an important issue of widespread concern in the international community [2]. The current data show that China's existing building energy consumption accounts for about 33% of the total social energy consumption. Among the buildings owned, buildings with high energy consumption account for a large proportion. Due to the increase of such buildings, the crisis of energy shortage has been aggravated [3]. According to the existing data, China now has a construction area of nearly 40 billion square meters, 90% of which belong to high energy consumption buildings [4]. The energy consumption of heating ventilation air conditioning (HVAC) system accounts for more than half of all building energy consumptions. Although the heat given by heating per unit area of buildings in China is three times that of advanced national buildings, the degree of comfort brought to users during heating period cannot meet people's expectations [5]. Therefore, the optimization research of intelligent HVAC in urban buildings has become an urgent scientific problem to be solved in this field [6]. The optimization of HVAC system design can not only reduce the energy loss of HVAC system, but also provide happier living space for indoor users.

The data information in building information model (BIM) technology can provide data support and basis for judging green building performance and quality. BIM describes the characteristics of buildings in a data-based way, which can provide the data of buildings at all stages of the project [7]. As artificial intelligence technology develops rapidly, various algorithms can effectively optimize the system, and then achieve the energy consumption reduction [8]. Among them, Shalabi and Turkan (2017) improved the data required for air conditioning system maintenance by using the visualization and operability functions of BIM. The results showed that the system could effectively feedback the fault data of air conditioning equipment to the control platform, and reduce the increasing energy consumption cost caused by continuous operation of equipment due to fault [9]. Afram et al. (2017) designed the predictive control system based on the artificial neutral network (ANN) model, and found that the model could significantly reduce the operating cost of HVAC equipment without affecting the system performance [10]. Ghahramani et al. (2017) optimized the HVAC system in industrial buildings assisted by genetic algorithm. The optimized system ensured the daily minimum energy consumption and the thermal comfort of air conditioning [11]. Sporr et al. (2019) designed a HVAC control system based on the building information data in BIM. The system could improve the existing control system, thus optimizing the operation energy consumption of building air conditioning equipment [12]. Based on the above studies, it is found that if only the supply of the main power grid and gas network is relied on to meet the needs of users, for the supply side, the energy utilization rate is extremely low, and huge power supply pressure is caused during the peak period of energy consumption, which shortens the service life of the power grid and endangers the security of power supply. On the demand side, it will also increase the power consumption cost and cause certain losses to the electrical equipment.

In order to deal with the above problems, based on the in-depth analysis of the existing HVAC system problems, effective solutions are put forward. The integrated back propagation neural network (BPNN) and Adaboost algorithm are used for HVAC system research, and targeted energy saving and emission reduction is carried out. BIM technology is used to simulate the HVAC system of urban buildings, and construct the appropriate optimization programme. The design of HVAC system based on this programme can not only solve many problems existing in the current design process of traditional air conditioning system, but also improve the efficiency of HVAC specialty and other related specialties in the design process, so that HVAC plays a more important role in the exploration of energy-saving building design.

There are five sections in total. The first section is the introduction, which explains the advantages of the heating and ventilation system and the necessity of its research. It also discusses previous studies and clarifies the differences of this investigation. The second section introduces the research method, such as the energy consumption prediction algorithm of the HVAC system, the BIM technology, the HVAC system optimization design based on BIM technology, and the air conditioning system's energy consumption simulation process described by the Adaboost-BP algorithm. The third section presents the results, which explains the performance of the Adaboost-BP prediction algorithm and analyzes the energy consumption of the HVAC system. The fourth section is the discussion, which compares the obtained results with the state of the art algorithms in previous works and probes into the possible problems of the system. The fifth section is the conclusion, which explains the principal contributions and limitations in detail.

2. Method

2.1. Energy consumption prediction algorithm for HVAC system

(1) Adaboost algorithm: The integrated learning algorithm is a research focus in machine learning algorithms. In the integrated learning algorithm, the enhanced learning algorithm is one of the commonly used algorithms. Adaboost algorithm (adapted boosting) is the most popular one in the current meta-algorithm and widely used in various classification prediction problems [13]. Adaboost algorithm has a low generalization error rate, and can be implemented by coding, which is suitable for most classifiers without parameter adjustment. However, this algorithm has a running time field and is more sensitive to outliers. To some certain extent, the algorithm relies too much on the training data and the selection of weak classifiers, which means that when the training data can't satisfy the algorithm, the classification performance of the weak classifier is not high enough, and the classification effect of the algorithm will also become worse [14].

The Adaboost algorithm will first give the same initial weight value to each sample in the training dataset and convert the weight value into a vector. The training sample data are used to train the established weak classifier, the error rate of the classifier is obtained, and then the weak classifier is trained again through the training dataset. Based on the obtained error rate, the weight of the sample in the training data is adjusted to reduce the weight value of the accurate sample data of each classification, and the weight value of the wrong sample data is improved. The weight is adjusted to transform the weak classifier into a strong classifier and reduce the error rate of classification, and the algorithm is characterized by eliminating interference and high training pertinence.

However, due to the high dependence of the algorithm on the training data and the performance of the classifier, it is easy to fall into local minimum. While BPNN is a multi-layer feedforward neural network algorithm based on error back propagation and it has high nonlinear mapping ability, self-learning, and adaptive ability. Meanwhile, the generalization performance is also relatively excellent, which can meet the demand of Adaboost algorithm for weak classifier and improving BP algorithm is easy to fall into the disadvantage of local minimum [15].

(2) BPNN algorithm: Generally, BPNN mainly includes input layer, hidden layer, and output layer. The original data are input into the input layer of BPNN, and the calculation results are obtained through the calculation of the hidden layer and the output layer [16]. When BPNN is used for calculation, the weights and thresholds between levels are adjusted by means of back propagation of errors, and the calculation results are not output until the calculation results meet the error range or reach the maximum number of iterations. The number of nodes in each hierarchy of BPNN is multiple, among which the number of nodes in the input layer is determined by the data characteristic variables contained in the data sample, and the number of nodes in the output layer is determined by the number of sample classification. The number of hidden layers can have multiple layers, and each layer can contain one or more nodes. However, the number of layers and the number of nodes of this layer are determined through subjective experience, and then adjusted through the data calculated later. The calculation method is shown in (1).

$$m = 2n + 1 \tag{1}$$

In (1), n is the number of input nodes, and m is the number of nodes in the output layer.

With the increase of the number of network layers, the complexity of BPNN also increases, and meantime, it will also lead to a decrease in the accuracy and speed of the algorithm [17]. Therefore, the neural network algorithm with the total number of network layers of 3 layers is selected in experiment. The number of nodes in the hidden layer h of BPNN is as follows:

$$h_i = f_1(\sum w_{ij} + b_i) \tag{2}$$

Then, the calculation method of neuron node number y in the output layer is as follows.

$$y_k = f_2(\sum w_{jk} + b_k) \tag{3}$$

In equations (2) and (3), w_{ij} is the initial weight value between the input layer and the hidden layer, w_{jk} is the initial weight value between the hidden layer and the output layer, f_1 and f_2 refer to the transfer functions between the input layer and the hidden layer, and between the hidden layer and the output layer, and b_i and b_k are the thresholds of the hidden layer and the output layer, respectively.

(3) Adaboost-BP algorithm: BPNN has the characteristics of strong classification ability, which can meet the requirements of Adaboost algorithm with strong dependence on the classifier, and Adaboost algorithm can improve BPNN from falling into the local minimum. Therefore, Adaboost-BP algorithm is combined with these two algorithms to

predict the energy consumption of building HVAC system [18]. The prediction flow of the combined algorithm is shown in Figure 1 below.

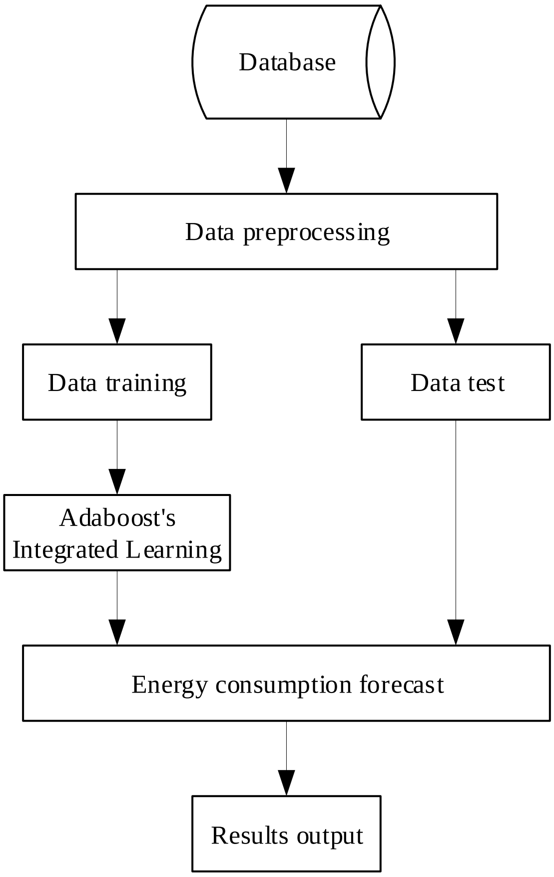


Fig. 1. Flow chart of system energy consumption prediction based on Adaboost-BP algorithm

When Adaboost-BP algorithm is used for energy consumption prediction, the data is prepared first. A total of S group training datasets is randomly extracted from the original sample datasets, and then the datasets give the initial weight values. The method is shown as (4).

$$Q_i = \frac{1}{S}, i = 1,2,\cdots s \tag{4}$$

In (4), *i* refers to the sample dataset, and Q is the initial weight value of the dataset.

According to the characteristic number (dimension) of the training data, BPNN is built, and the initial weight and threshold value of each node are given in the neural network.

It is also necessary to establish a weak classifier. The method is to establish a BPNN weak classifier of the corresponding value through the cycle coefficient N required by the algorithm. Next, the error rate of the established weak classifiers is calculated, and according to the error rate, the initial weight value of the weak classifier is calculated. The calculation method is shown as follows.

$$\alpha = \frac{1}{2}\ln(\frac{1-\varepsilon}{\varepsilon}) \tag{5}$$

After obtaining the initial weight value of each sample, it is necessary to adjust the weight value, reduce the weight value of the sample with correct classification, and increase the weight value of the sample with wrong classification.

After adjusting the weight value, Adaboost continues the next round of loop iteration. During the loop iteration, the training sample data is repeatedly trained, and the weight value of the sample is constantly adjusted until the classification error rate of the sample reaches the allowable range or reaches the maximum number of loop iterations. These weak classifiers are combined to form a strong classifier. The calculation method is shown as follows.

$$G(x) = sign(f(x)) = \left\{ \sum_{m=1}^{M} \alpha_m G_m(x) \right\} \tag{6}$$

In (6), m is the number of layer nodes, and Gm(X) is the weak classifier.

2.2. BIM tecnology

BIM technology uses all data parameters in the engineering project to build the physical model of the building, and converts the information related to the building into data for storage. It can store and simulate all the data of the project from the planning to the completion of the construction. It provides scientific basis for the decision-making of relevant personnel, changes the working form of the project construction, improves the construction efficiency of the construction project, and reduces the risk of the project construction [19]. With the further development of information technology, BIM technology has also updated drawing software tools and improves the connection and interoperability of data information during project construction. From the perspective of building standards, BIM technology digitally expresses all data related to the project and BIM technology has the characteristics of visualization, datalization, coordination, and simulation [20].

Visualization refers to the building entity model established by using BIM technology, which can directly express all the processes of the project from planning and design to construction, and then to operation and maintenance through simulation, showing the design effect diagram. Relevant personnel can discuss and modify the project design, construction, operation, and maintenance phase of the programme at any time. Datalization is mainly about the data management of the relevant information generated by the project. By using BIM technology, project data can be quickly and efficiently calculated and processed, the construction progress of the project can be accelerated, effective calculation and digital information can be provided for the project, and scientific and reasonable simulation analysis can be carried out for the project meantime. Therefore, the management of the construction project is more precise, scientific, and meticulous. Coordination means that BIM technology can be used for collaborative design. Before the project construction, the design programme involved in the project can be simulated through BIM and then integrated. It can find the contradictions in the construction process of the project as early as possible, help relevant personnel to find the problems fast, formulate reasonable solutions, and improve the work efficiency of the project. Simulation means that BIM technology can not only simulate and analyze project engineering, but also simulate application research to a certain extent. BIM can analyze and simulate the requirements of the whole project, such as energy conservation needs, security needs, and comfort requirements. It can make 3D simulation of the construction site, thus facilitating the planning and design of scientific, reasonable construction plans and guidance programmes. Additionally, it can also carry out 5D simulation analysis to help the relevant personnel to control the project cost [21].

BIM technology has professional value, information value, and management value. Professional value means that the technology can deepen and optimize the projects involved in construction projects, information value mainly means that the data generated in the project could be stored, analyzed and managed, and management value means that relevant personnel can optimize and control their professional value and information value to improve efficiency [22].

2.3. Optimization design of HVAC system based on BIM technology

To some extent, the optimization of HVAC system can promote the energy conservation of buildings and improve the design level of HVAC system. The simulation of HVAC system by using BIM technology can directly present the energy consumption of building HVAC system. Moreover, different data information can be used to carry out simulation and compare the energy consumption of the HVAC system under different conditions, thereby selecting the best design programme of the HVAC system. Furthermore, the technology has a good docking, and can be connected with a variety of software, and directly passes the software system data for simulation. The information data of the optimized air conditioning system can reflect that the system guides BIM to conduct modeling of the air conditioning system, and then the data of the optimization results and simulation results of the air conditioning system can be stored to facilitate the later invocation [23]. The optimization process of air conditioning system using BIM is shown in Figure 2 below.

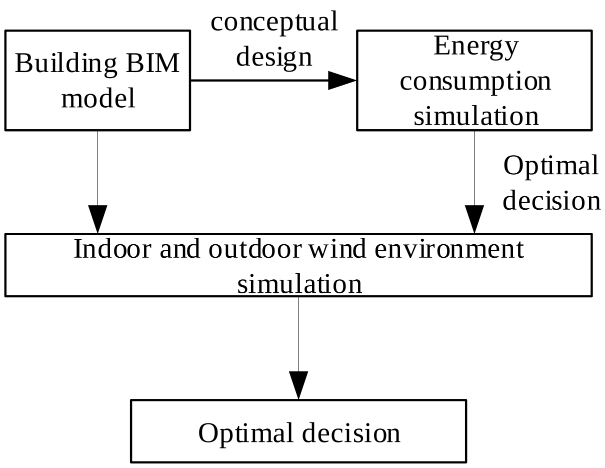


Fig. 2. Optimization process of air conditioning system based on BIM technology

The HVAC system is used to ensure that the indoor temperature is suitable by means of system cooling or heating. Meanwhile, the system can also improve the indoor air circulation, ensure the smooth exchange between the outside and the indoor air, improve the indoor air environment, and improve the air quality [24]. The energy consumption of HVAC system is mainly produced by three parts: heating system, ventilation system, and HVAC system energy consumption, and the energy consumption of HVAC system is mainly related to HVAC system. Energy consumption modeling using BIM technology is mainly based on the characteristics of the building, and the corresponding mathematical equation and computer software are used to simulate the energy consumption of the building.

2.4. Simulation of energy consumption of air conditioning system based on BIM combined with Adaboost-BP algorithm

BIM technology and Adaboost-BP algorithm are used to simulate the energy consumption of HVAC system in urban buildings in experiment. Common BIM design platforms include Autodesk Revit, ArchiCAD, and Bentley, and the most widely used Autodesk Revit design platform is selected in experiment. The design platform supports the creation of architectural models, structural models, and electromechanical system models [25].

In the design of HVAC system, parameters such as indoor and outdoor wind environment and sunshine environment should be considered to optimize the design of building HVAC system. During the design process, computational fluid dynamics (CFD) is also used to calculate the discrete distribution of the fluid flow field in the region and to simulate the fluid flow [26].

Taking commercial buildings as an example, in the system design, BIM technology is first used to model the buildings. All the data information of the construction project is imported into the BIM, the geographical environment, indoor and outdoor meteorological parameters will affect the energy consumption of HVAC system, and indirectly cause the final analysis error. Therefore, it is necessary to analyze outdoor meteorological parameters, including outdoor wind speed, relative temperature, and humidity [27]. In addition, it is necessary to simulate the annual cold and hot load of the building, calculate the maximum cold and hot load value, and then set the temperature of the building HVAC system according to the corresponding load value. The main purpose in experiment is to simulate the variable air volume (VAV) system. Three different VAV systems are shown in Table 1 below.

Table 1. Performance comparison of different VAV air conditioning systems

Programme	VAV system end unit	Characteristic	Advantage
1	VAV system in parallel fan power box	The end unit used electric, steam or hot water to heat the coil to gain additional heat	Good flexibility, quiet operation, waste heat recovery, night return operation
2	Mixed cooling beam + VAV reheating system	Air processor with external constant volume	Improving air quality
3	VAV system with reheating system	Heating occurred primarily or exclusively at the regional level, with cross flow control and additional heating and cooling to control the regional temperature	Reheating the end

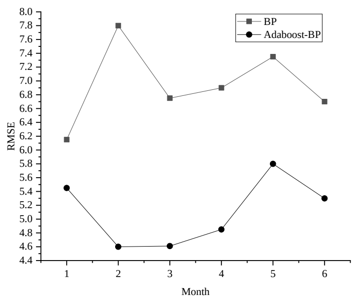
In addition, building HVAC systems will also increase CO_2 emissions, which will lead to the occurrence of the global greenhouse effect. Therefore, the CO_2 emissions of these programmes should be simulated and analyzed to optimize the overall air conditioning system.

3. Results

3.1. Performance analysis of Adaboost-BP prediction algorithm

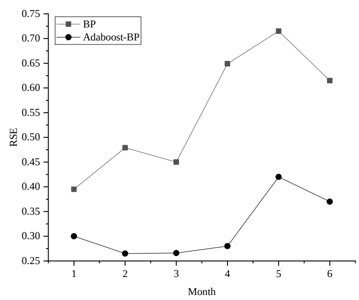
In order to verify the performance of the energy consumption prediction algorithm studied in experiment, the prediction accuracy of the traditional BPNN algorithm and Adaboost-BP algorithm is compared from the predicted root mean square error (RMES), relative square root error (RSE), and overall accuracy (OA). The comparison results are shown in Figure 3 below. OA of BPNN monthly energy consumption forecast is between 81.16% and 89.89%. The prediction effect of January is the best, which can reach 89.89%, while that of March is only 81.16%. However, the overall monthly accuracy of Adaboost-BP is improved to 85.91% - 90.31%. It shows that compared with the single BPNN, Adaboost-BP algorithm reflects a higher overall accuracy, and for the prediction model with low accuracy of weak classifier classification effect, such as February and March, it shows better improvement effect. This is directly related to the parameter setting characteristics of Adaboost ensemble learning algorithm. Adaboost algorithm has low requirements for weak classifier, and hardly needs to adjust the parameters of weak classification, which is another reason why Adaboost BP algorithm is widely used.

(a)



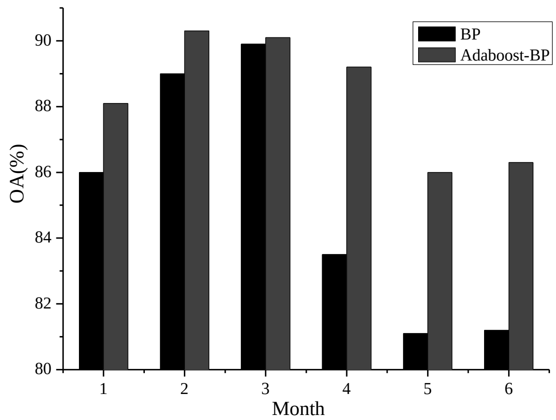
RMSE comparison of the two algorithms

(b)



RSE comparison of the two algorithms

(c)



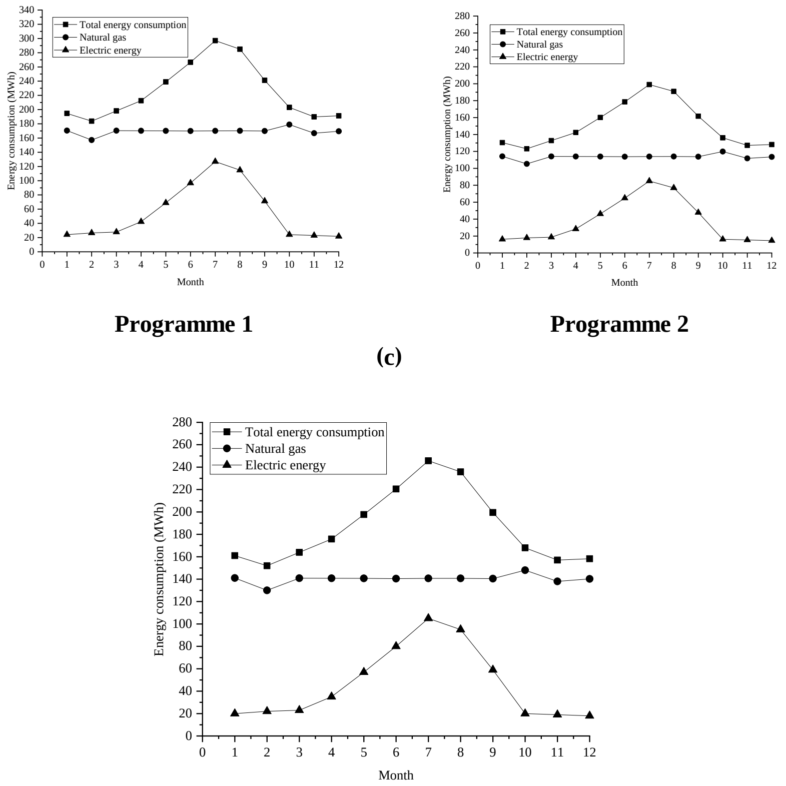
Overall accuracy comparison results of the two algorithms

Fig. 3. Comparison results of prediction error accuracy of the two algorithms

3.2. Energy consumption analysis of different HVAC systems

The total energy consumption, natural gas, electric energy and boiler energy consumption of three programmes of HVAC system are analyzed and calculated to save energy consumption and reduce energy waste, and the optimal programme is found out. The optimal design is carried out by using the programme system. The analysis results are shown in Figure 4 below. Figure 4 suggests that the power consumption and gas consumption of the programme 2 are the lowest. During the operation, the operation cost is lower than that of programme 1 and programme 3. Compared with programme 1 and programme 3, energy consumption is saved by 33% and 19%, respectively. Moreover, in terms of cost, the programme 2 also saves money. Compared with the programme 1 and programme 3, the cost is saved by 37% and 15%, respectively.

(a) **(b)**



Programme 1 **Programme 2**

(c)

Programme 3

Fig. 4. Energy consumption analysis of different HVAC systems

When the system is designed, it not only considers the energy consumption of the system, but also considers the system cost and the emission of CO_2. The analysis and calculation results of energy consumption cost and CO_2 emission of each programme are shown in Figure 5 below. Figure 5 shows that the CO_2 emission of the programme 2 is the lowest, which is 60% lower than that of programme 1 and 31% lower than that of programme 3. The programme 2 is the best in terms of energy consumption and the impact on the environment, so the programme 2 is selected as the optimal programme, and the information of the selected air conditioning system is fed back to the Revit MEP model to establish the optimal air conditioning system model.

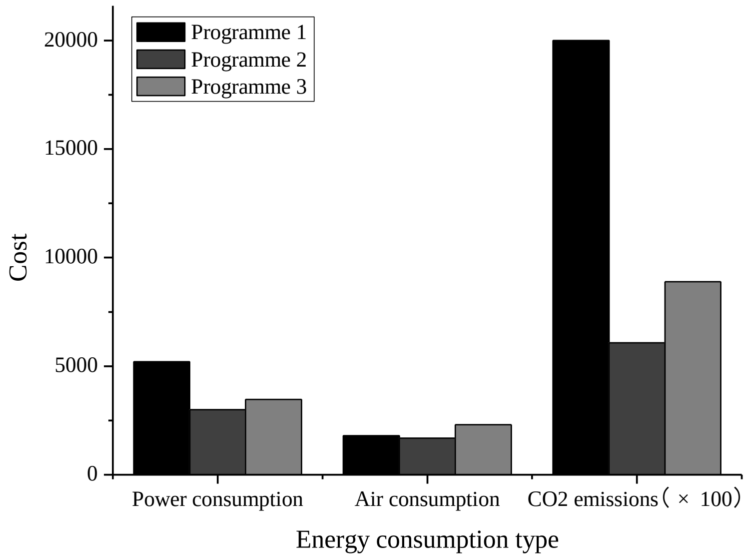


Fig. 5. Analysis results of energy consumption values and CO_2 emissions of different programmes

4. Discussion

First, based on BPNN algorithm, according to the previous research, it is found that the algorithm has some limitations, such as poor generalization ability and easy to fall into local minimum value. Therefore, a building integrated learning energy consumption prediction model based on Adaboost-BP algorithm is constructed by using Adaboost ensemble learning algorithm. It is found that the model has higher accuracy than the single BPNN, and it has better performance for the prediction model with low accuracy of weak classifier classification effect (Figure 3), which is consistent with the research results of Lu et al. (2017). Adaboost algorithm is used to improve BPNN. The life predicted by the improved method is compared with the traditional BPNN. Different power levels of light emitting diode (LED) lamps are compared. It is found that the average relative error of the improved method is reduced by 54%. However, the improved method takes 63.6% longer running time [28]. However, the measured operating time does not decrease much, which may be because the HVAC system has been in operation.

In addition, regarding the energy saving measures of HVAC system based on BIM technology, building envelope energy saving, air conditioning system scheme comparison and indoor and outdoor wind environment analysis, energy saving of HVAC system is studied. The programme 1 is to use water chilling unit and cooling tower in summer. In winter, the hot water boiler mode is used for heating, and the parallel fan power box mode of variable air volume system is adopted at the end. This mode provides great flexibility to meet the design requirements of various HVAC systems. This method has been reported in reference [29]. The programme 2 is to use the combination of water chilling unit and cooling tower in summer, hot water boiler mode in winter, and hybrid cooling beam + variable air volume reheating system at the end. The design of this system includes two external constant volume air processors to improve the quality, which has also been reported in reference [30]. In the programme 2, water cooling units and cooling towers are used in summer, and hot water boiler mode is used in winter. The variable air volume system with reheating system is used at the end of the system. Moreover, heating and cooling the air provided to the laboratory is to control the temperature and humidity, which is also more common [31]. BIM technology is used. Three programmes are dsicussed, the optimal HVAC programme is obtained and compared with other programmes, and the energy consumption of hybrid cooling beam + variable air volume reheating system is reduced by about 30%, which provides a new programme for HVAC system, and it is determined by energy consumption simulation, which is also mentioned in reference [32].

5. Conclusion

The energy consumption of building HVAC system is predicted by combining BPNN and Adaboost algorithm to form Adaboost-BP algorithm. Then, the relevant concepts of BIM technology are introduced, and the design of HVAC system is optimized based on BIM technology. Finally, the energy consumption of different HVAC systems is simulated by using BIM model combined with Adaboost-BP algorithm. Adaboost-BP algorithm can improve BPNN, which is easy to fall into the local minimum, and improve the classification effect of the weak classifier. The prediction error of this algorithm is smaller and the accuracy is higher. The BIM model combined with Adaboost-BP algorithm are used to simulate the energy consumption of three HVAC systems, and the results show that the HVAC system with mixed cooling beam and VAV reheating has the least power consumption and air consumption, and the CO_2 emission is reduced. Therefore, it is used as the optimization programme of HVAC system. The result shows that the Adaboost-BP algorithm can be used to predict the energy consumption of the air conditioning system. The HVAC system with mixed cooling beam and VAV reheating can reduce the energy consumption of the air conditioning system and the CO_2 emissions, so it can be used as the optimization programme of the HVAC system.

Only three different VAV systems are selected to conduct research when modeling air conditioning energy consumption using BIM technology, and the programmes are relatively few. Meanwhile, when modeling energy consumption, only some factors affecting building parameters are selected, which lack certain comprehensiveness. It is hoped that in the following work, factors causing interference to the building HVAC system can be fully considered for a comprehensive analysis, thus improving the comprehensiveness of the research. Due to the limitation of conditions, the results of the optimization programme are only based on theories, and lack certain practicality. It is hoped that it can be demonstrated in the subsequent research, and the feasibility of programme can be studied.

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