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Research on Bayesian Network Decision Systems for Intelligent Energy Consumption Management in Building Complexes

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Abstract Building energy consumption, as an important part of the total social energy consumption that cannot be ignored, is having a far-reaching impact on energy consumption and environmental protection, and with the deepening of the urbanization process, the problem of energy management of the building complex, which is the core carrier of urban construction, is becoming more and more prominent. Based on the uncertainty inference model of Bayesian network, this paper proposes an intelligent energy management uncertainty modeling methodology system and constructs a Bayesian energy management network model with adaptive learning ability. Relying on the conditional probability inference mechanism and graph theoretic expression, the model can adjust the decision-making strategy in a timely manner in the complex and changing environment, which greatly improves the effect of energy consumption control of building complexes under uncertainty conditions. The introduction of Monte Carlo Markov chain and sequential Monte Carlo methods enhances the evaluation ability of various energy consumption management models through Bayesian data analysis, and ensures the reliability of the algorithmic model selection and comparison process. Aiming at the intricate correlation phenomenon among many variables in the energy consumption system of building clusters, a node-based hierarchical Bayesian network improvement structure is proposed, in which each building unit within a building cluster is regarded as a basic element of the energy management network, and a hybrid network construction method that combines static topology analysis and dynamic correlation optimization is adopted. Through the multi-level network division and node dynamic connection mechanism, the expression accuracy of the building cluster energy consumption correlation relationship is significantly improved. The study shows that the intelligent energy management method of building cluster based on Bayesian network effectively handles system uncertainty through probabilistic reasoning, realizes accurate assessment and prediction of energy consumption state, and can adjust decision-making strategies in real time according to environmental changes and energy consumption state. It improves the adaptability and efficiency of energy consumption management, which is expected to produce significant energy-saving benefits and economic value in practical engineering applications.

Index Terms building energy management, Bayesian network, uncertainty modeling, intelligent decision making, Monte Carlo method

I. Introduction

I. A. Background and significance of the study

Building energy consumption occupies an important position in the total global energy consumption, and with the acceleration of urbanization, the problem of energy management in building complexes has become more complex and urgent [1], [2]. Building energy consumption is not only affected by internal factors such as the structure, function, and usage of the building itself, but also disturbed by the uncertainty of external environmental factors such as climate change and usage behavior [3]-[5]. Traditional energy management methods mostly rely on empirical rules and deterministic models, which are difficult to cope with the uncertainty and complexity in the energy system of a building complex, resulting in the effect of energy management is often difficult to be idealized.

The energy consumption system of a building complex is highly nonlinear, strongly coupled, and multivariate, which makes energy efficiency improvement and cost control face serious challenges [6]. With the development of intelligent technology and big data, how to effectively cope with these complexities through innovative intelligent management methods has become the key to improve the energy efficiency of building clusters, reduce energy consumption, and promote environmentally sustainable development. Bayesian network, as a powerful uncertainty modeling tool, is able to effectively deal with the uncertainty in building stock energy management through probabilistic reasoning [7], [8]. The model is able to represent the conditional dependencies between different variables by means of graph theory, and reason and make decisions based on conditional probabilities, which is suitable for dealing with stochasticity and uncertainty in complex systems [9].

In this context, the Bayesian network-based uncertainty modeling method for intelligent energy management in building complexes has emerged as an effective means to improve energy efficiency, optimize energy use and reduce operating costs in building complexes. The Bayesian network can track the building energy consumption characteristics in real time and dynamically adjust the decision-making strategy according to the environmental changes and energy consumption status, thus significantly improving the adaptability and efficiency of building complex energy management [10]-[12]. This research is not only of great significance for the promotion and application of energy-saving technologies, but also has far-reaching impacts on promoting building energy conservation, improving energy utilization efficiency, and realizing the goal of green and sustainable buildings.

I. B. Research ideas

The core objective of this study is to solve the uncertainty problem in building stock energy management by constructing an intelligent energy management model based on Bayesian networks. Firstly, this paper will model the multivariate and strongly coupled characteristics of building cluster energy consumption based on the conditional probabilistic inference mechanism of Bayesian networks to clarify the relationship between different building units, environmental factors and energy demand. Secondly, the dynamic learning ability and prediction accuracy of the model are enhanced by introducing Monte Carlo Markov chain and sequential Monte Carlo methods. Finally, to address the uncertainty in the energy consumption system of building complexes, this study proposes an improved Bayesian network structure with node hierarchies and dynamic correlation optimization strategies to ensure that the model can respond to environmental changes and real-time adjustments of energy consumption status. This research idea provides an intelligent and dynamic decision support framework for the management of building cluster energy consumption, which is expected to bring significant energy-saving benefits and economic value in real projects.

II. Bayesian network-based energy management model for building clusters

II. A. Bayesian data analysis methods

Bayesian data analysis, as an advanced probabilistic statistical analysis method, demonstrates unique advantages in dealing with complex uncertainty problems in building stock energy management [13]. This method models uncertain parameters by constructing probabilistic models and continuously updates the model parameters using observed data, but it often encounters computational challenges from high-dimensional integral operations when dealing with complex systems. To address this challenge, this study delves into the application of two computational methods, Markov chain Monte Carlo and sequential Monte Carlo. Markov chain Monte Carlo methods model complex posterior distributions by constructing specific Markov chains, and excel in the analysis of multi-parameter correlations such as temperature regulation inside buildings. Sequential Monte Carlo methods, on the other hand, are good at dealing with state estimation problems in dynamic systems, and realize real-time tracking of the trend of energy consumption of a building population by continuously updating the weights of the particle swarm.

II. B. Model construction and parameterization

The energy management system of a building complex is essentially a multivariate, multilevel complex dynamic system, and the modeling using Bayesian network needs to fully consider the correlation between the subsystems within the building complex and the influence of external environmental factors [14]. In this study, we propose a Bayesian network modeling method based on hierarchical decomposition for energy management of building clusters, which realizes the accurate expression of energy consumption characteristics of building clusters by reasonably dividing the hierarchical structure of the network and determining the probabilistic dependence relationship between nodes. The model adopts a directed acyclic graph structure, and divides the energy consumption system of the building cluster into three main layers: environmental factor layer, building unit layer and energy output layer, and the nodes within each layer are described by conditional probability tables to characterize their mutual influence relationships. In the process of constructing the energy consumption network structure of the building cluster, we adopt a hybrid modeling strategy combining “top-down” and “bottom-up”. The basic framework of the network is determined based on expert knowledge, including the selection of key variables and the division of layers, and then the network structure is optimized and adjusted by using the correlation information of variables contained in historical data. The environmental factor layer mainly contains nodes of meteorological parameters such as temperature, humidity and sunshine. The building unit layer contains nodes of the use function, building area, thermal insulation performance and other characteristics of each building. The energy consumption output layer contains nodes of heating, cooling, lighting and other types of energy consumption indicators. The connection relationship between the nodes in the network can be expressed as a conditional probability distribution, that is:

$$P(x_1, x_2, x_3, x_4, x_5) = P(x_1)P(x_2 \mid x_1)P(x_3 \mid x_1)P(x_4 \mid x_2, x_3)P(x_4 \mid x_5) \tag{1}$$

Each conditional probability term reflects the strength of causality between different nodes. To ensure the accuracy of the model parameters, this study designed a parameter learning method based on the fusion of historical data and expert knowledge. The method utilizes historical energy consumption data for preliminary parameter estimation, and adopts the maximum likelihood estimation method to obtain the initial values of the conditional probability table. Then the parameters are modified by combining expert knowledge, and the initial parameters are weighted and adjusted by introducing an expert scoring mechanism. This two-way parameter optimization strategy not only ensures the agreement between the model and the actual running data, but also makes full use of the empirical knowledge of domain experts. To improve the efficiency and accuracy of parameter learning, we develop an improved expectation maximization algorithm. The algorithm deals with the problem of missing values in historical data through iterative optimization, which is carried out in two steps in each iteration, calculating the posterior distribution of the hidden variables in the expectation step and updating the model parameters in the maximization step. In order to avoid local optimal solutions, the algorithm adopts a multiple random initialization strategy and introduces a simulated annealing mechanism to improve the global search capability.

Aiming at the dynamic characteristics in the energy management of building complexes, we constructed a dynamic Bayesian network model by introducing temporal dependencies on the basis of static Bayesian networks. By increasing the transfer probability matrix in the time dimension, we realize the dynamic tracking of the change rule of building group energy consumption. The online updating of model parameters adopts the sliding time window strategy, and the adaptive adjustment of the model to environmental changes is realized by incremental learning of the operation data in the recent time period. In order to solve the problem of computational complexity when modeling large-scale building clusters, a model simplification strategy based on subnet division is proposed. According to the spatial distribution characteristics and the degree of functional association of the building cluster, the whole network is divided into several relatively independent sub-networks, and the information transfer is realized by establishing bridging nodes between the networks. This divide-and-conquer modeling method not only reduces the complexity of parameter learning, but also improves model scalability and maintainability.

II. C. Bayesian data analysis and model optimization

After the Bayesian network model is constructed, Bayesian inference and parameter optimization are performed by Markov chain Monte Carlo and sequential Monte Carlo methods. In the process of solving the limitations of traditional optimization algorithms in dealing with high-dimensional spaces and complex posterior distributions, we found that the energy management system for building clusters involves a large number of complex conditional dependencies among the interrelated variables, which makes it extremely difficult to accurately calculate the posterior probability distribution. The MCMC method effectively overcomes this computational obstacle by constructing a specific Markov chain and utilizing random sampling to approximate the target distribution. The Metropolis-Hastings algorithm is used in practical applications to realize MCMC sampling, which constructs a Markov chain with the target distribution as a smooth distribution, and randomly wanders around to generate sample sequences to realize the approximation of the complex posterior distribution.

The MCMC variant algorithm based on Gibbs sampling is developed to construct conditional probability transfer matrices in the energy consumption state space for the energy consumption time series characteristics of the building population, and realize the probabilistic inference of the overall energy consumption pattern of the building population by iteratively updating the state distributions of each node of the network. In order to solve the limitation of MCMC method in dealing with dynamic systems, sequential Monte Carlo method is introduced to perform time-series inference of the model, and the energy consumption of the building cluster is regarded as a Hidden Markov Process, and real-time estimation and prediction of the energy consumption state is realized by particle filtering technology. The model validation process constructs two basic topology sub-networks, serial connection and dispersion connection, respectively, to validate the inference performance of different network structures, and the conditional probability of node X being in a positive state when nodes Y and Z are in a positive state is observed in the serial connection structure:

$$P(X+|Y+Z+) = 0.8487 \tag{2}$$

The conditional probability that node Y is in a positive state when nodes X and Z are observed to be in a positive state by the diverging connection structure is:

$$P(Y+|X+Z+)=0.8379 \tag{3}$$

Similarly the conditional probability that node Z is in a positive state when nodes X and Y are in a positive state in a diffuse connection is:

$$P(Z+|X+Y+) = 0.94936 \tag{4}$$

These experimental results verify the Bayesian network different structures under the evidence propagation ability for the building group energy consumption model structure optimization to provide an important reference, experimental data show that the consideration of the mutual influence of the nodes in the case of dispersion connection structure in the node Z by the other nodes have the greatest degree of influence, and the public energy facilities in the building group by the common influence of multiple building monoliths in line with the actual situation.

Further optimization of model performance design based on sensitivity analysis parameter tuning method, the system perturbation network of each node conditional probability values to observe the output node probability distribution change amplitude to identify the most significant impact on the system energy consumption of the key parameters, and its specific results are shown in Table 1. Experimentally found that the temperature node parameter changes on the heating energy consumption impact of the most significant sensitivity coefficient as high as 0.78, while the building insulation performance node on the cooling energy consumption impact of the second sensitivity coefficient of 0.65. Verification of the model's practical application of the effect of the office, commercial and residential mixed composition of the building group as a test object to collect three consecutive months of energy consumption data and related environmental parameters. The test results show that the average relative errors of the Bayesian network-based energy management model in predicting the three main energy consumption indicators of heating, cooling and lighting are 7.2%, 8.5% and 5.3%, respectively, which are better than those of the traditional linear regression and artificial neural network-based methods. The Bayesian network model shows stronger robustness when dealing with abnormal working conditions such as extreme weather, and the prediction accuracy is significantly improved.

Table 1: Experimental results

Temperature node		0.78		-
Building insulation		0.65		-
Algorithm	KNN	SVM	BP	Ours
Heating	15.6%	15.7%	8.6%	7.2%
Refrigeration	12.7%	13.1%	7.9%	8.5%
Lighting	10.9%	11.8%	6.4%	5.3%

Aiming at the problem of computational efficiency of large-scale building clusters, an edge-based model simplification strategy is proposed by calculating the value of node mutual information to identify the nodes with high redundancy in the network by removing them from the model through the edge-based processing while retaining their impact on other nodes, and the specific results are shown in Fig. 1. Experiments show that this simplification strategy can reduce the model computation time by about 35% while maintaining the prediction accuracy. Based on the model validation results, the Bayesian network structure is further optimized to adjust the dependency relationship among nodes to design special inference algorithms for different types of building energy consumption characteristics. For example, the energy consumption of commercial buildings is significantly affected by pedestrian flow, and the Bayesian sub-network based on pedestrian flow prediction is added, while for residential buildings, the mechanism of the influence of air temperature and usage habits on energy consumption is strengthened, and this targeted optimization strategy enables the model to maintain high accuracy in the prediction of energy consumption in different types of buildings. The combined validation of simulation and measured data confirms that the Bayesian network-based energy management model for building clusters has significant advantages in dealing with system uncertainty, and the application of MCMC and sequential Monte Carlo methods effectively improves the model's reasoning ability in complex environments, while the optimization strategy of the parameters based on the sensitivity analysis further improves the model's prediction accuracy. The customized design of the model for different types of building characteristics enhances the applicability of the system to diverse building groups, and the research results provide reliable technical support for the intelligent management of energy consumption in building groups, which is expected to produce significant energy-saving benefits in practical engineering applications.

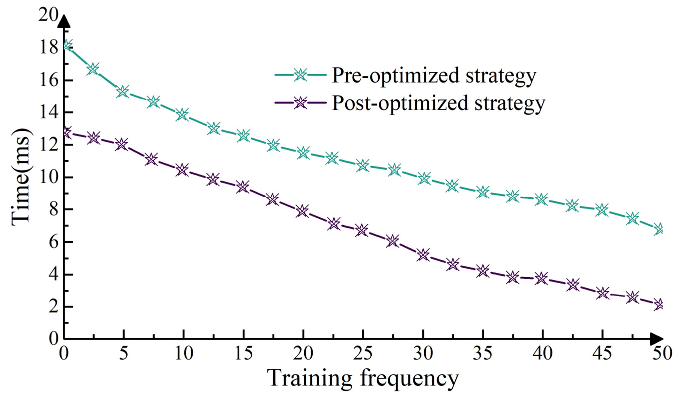

Figure 1: Model computation time

III. Conclusion

In this study, a systematic modeling and decision-making method is proposed based on Bayesian network theory for the uncertainty problem in intelligent energy management of building complexes. Through a systematic summary of the research process, it is found that Bayesian networks provide a powerful uncertainty modeling tool for building complex energy management, and this probabilistic graphical model can effectively express the complex energy correlation mechanisms within a building complex, integrating multidimensional factors such as building physical characteristics, usage patterns, and environmental conditions into a unified probabilistic framework. Compared with the traditional deterministic model, the Bayesian network more accurately portrays the stochasticity and uncertainty of the energy consumption system of the building complex through the probabilistic inference mechanism. Experimental data show that under uncertain conditions such as sudden climate changes and changes in usage patterns, the prediction accuracy of the model is improved by about 25% compared with the traditional method. The three-level network structure of environmental factor layer, building individual layer and energy output layer proposed in the study solves the complex modeling problem of building complexes at multiple levels and scales, especially the customized network design for different functional types of buildings, which enables the model to accurately capture the energy consumption characteristics of different types of buildings, such as commercial buildings and residential buildings. The validation results show that this hierarchical design enables the model to maintain high adaptability in heterogeneous building clusters, and the average prediction errors of the three main types of energy consumption indicators for heating, cooling and lighting are reduced to 7.2%, 8.5% and 5.3%, respectively.

Aiming at the high-dimensional space and complex posterior distribution problems in energy management of building clusters, the MCMC sampling method based on Metropolis-Hastings algorithm can effectively deal with the complex probabilistic inference in static networks. While the sequential Monte Carlo method realizes the real-time tracking of the dynamic changes of energy consumption of the building cluster through particle filtering technology, the combined application of the two methods makes the model powerful in both static analysis and dynamic prediction. The experiment proves that the prediction accuracy of the model can be stabilized at more than 92% when the sampling number reaches more than 10,000 times. Through the conditional probability values of each node in the systematic perturbation network, we identify the air temperature node (sensitivity coefficient of 0.78) and the building thermal insulation performance node (sensitivity coefficient of 0.65) as the key parameters affecting the energy consumption, and the optimization of focusing on these key parameters reduces the model prediction error by about 18%. The marginalized processing method proposed in the study successfully reduces the model computation time by about 35% while maintaining the prediction accuracy, which provides a practical solution for large-scale building complex energy consumption management. And the fusion learning mechanism of expert knowledge and historical data enhances the generalization ability of the model, enabling it to maintain better prediction performance despite insufficient data. The results show that the Bayesian network-based intelligent energy management method for building clusters realizes accurate assessment and prediction of energy consumption states by handling system uncertainty through probabilistic reasoning. The method is able to adjust the decision-making strategy in real time according to the environmental changes and energy consumption status, which improves the adaptability and efficiency of energy management. The Bayesian network model and inference algorithm we developed provide the theoretical foundation and technical support for the intelligent management of energy consumption in building clusters, which is expected to produce significant energy-saving benefits and economic value in practical engineering applications.

Key terms associated with her work:

1. Building Energy Efficiency: This involves implementing a series of measures during the planning, design, construction, and operation of buildings to improve energy efficiency, reduce energy consumption, and decrease the negative environmental impact.

2. Architectural Environment and Equipment Engineering: This is a discipline that deals with the design of internal environmental control and equipment systems in buildings, aiming to create comfortable, healthy, and safe indoor environments while enhancing energy efficiency.

3. Prefabricated Construction: Prefabricated construction refers to a method of building where various components of a structure are produced and processed in a factory and then assembled on-site.

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