Computer-aided Design and Implementation of Energy Efficiency in Buildings at the Conceptual Design Stage

Qing Zhou[1], He Zhan[2] and Gang Li[3*]

[1]Art and Design School, Liaoning Petrochemical University, Fushun 113001, China, 6163110014.edu@bkkthon.ac.th
[2]Bangkokthonburi University, Bangkok, 10170, Thailand, 6263210051.edu@bkkthon.ac.th
[3]School of Environmental Art, Shanghai Vocational College of Arts and crafts, Shanghai 201800, China, lgart@163.com

Corresponding author: Gang Li, lgart@163.com

Abstract. This paper adopts a computer-aided design approach to the conceptual design stage of building energy efficiency design, and proposes that the building energy consumption comparison evaluation model should fully reflect the complex correlation characteristics of building energy consumption based on the correlation analysis of building energy consumption influencing factors. In response to the problem of instability of the model structure that easily occurs in the conventional OLS-based multiple regression model, a multi-level test multiple regression modeling method based on the OLS method is proposed, and in response to the problem of poor accuracy of evaluation results due to the lack of statistical tests in the existing energy consumption evaluation, a method using double tests and distribution function tests is proposed, forming a systematic method for building energy consumption evaluation models. Under the policy background of structural reform, the energy consumption characteristics of public buildings are constantly changing, and determining the factors driving the changes is the key to establishing energy consumption models for public buildings. The preliminary screening of the driving factors of energy consumption characteristics of public buildings under structural reform and the comprehensive use of hierarchical analysis and entropy weighting method to assign subjective and objective weights to the driving factors of public energy consumption respectively effectively advance the study of control strategies for naturally ventilated buildings. Based on the simulation analysis of the control strategy influencing factors and their volatility patterns, the main predictable scenarios of natural ventilation in buildings are established: two composite ventilation scenarios considering indoor-outdoor temperature difference and humidity threshold respectively, and a pure natural ventilation scenario considering indoor-outdoor temperature difference and external window opening control logic.

Keywords: conceptual design phase; building energy efficiency; computer-aided; design and implementation
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1 INTRODUCTION

The comparison and evaluation of energy consumption in building operation are some of the important technical means to ensure the actual effect of energy saving. Unlike the design phase where simulated energy consumption is used to ensure the standard compliance of the design scheme, the evaluation of energy consumption in the operation phase uses the actual operating energy consumption of each project to evaluate, which directly reflects the actual energy consumption characteristics of the building. This "horizontal comparison" between similar buildings based on a large amount of actual data is far more practical than "vertical comparison" with itself. On the other hand, regular horizontal comparisons between buildings using updated actual operating data can also instantly reflect the actual effect of the promotion of building energy efficiency in society, forming a situation where "if you don't advance, you will fall back", encouraging buildings to continuously carry out energy efficiency improvement work, and realizing the sustainable development and virtuous cycle of building energy efficiency in society as a whole [1]. To meet the needs of different users and different application scenarios, the objects of building energy consumption comparison and evaluation can be divided into three categories: comparison and evaluation of total building energy consumption, sub-energy consumption, and equipment energy consumption. The application of the results of the three types of energy consumption comparison evaluation is different: the total energy consumption comparison evaluation points out the results of the overall energy consumption level of the building compared with similar buildings, so that the energy managers of the building, government authorities and other stakeholders understand the total energy consumption level of the building, providing a basis for the decision making of energy-saving work and the formulation of relevant policies, and facilitating the identification of target buildings for renewal and renovation; the itemized energy consumption comparison evaluation points out the results [2]. This allows building energy managers to identify systems with abnormal energy consumption and target systems for retrofitting; the equipment energy consumption comparison evaluation shows the results of each equipment's energy consumption compared to similar equipment, allowing building energy managers to identify equipment with abnormal energy consumption and target equipment for retrofitting. Mehndi used different scenarios for sensitivity assessment of the operating time, efficiency, and meteorological parameters of electromechanical equipment, and concluded that the energy estimation evaluation has a high degree of uncertainty, pointing out the need to strengthen energy management techniques [3].

The main purpose of this paper is to study the method of comparison and evaluation of energy consumption in public building operation and to establish a model using actual data to meet the technical requirements of comparison and evaluation of energy consumption at different levels in different application scenarios of energy conservation work in public buildings during the operation phase, to realize a comprehensive comparison and evaluation of energy consumption in public building operation, and to solve the evaluation methods of total energy consumption, sub-energy consumption and equipment energy consumption of buildings, in turn, to provide comprehensive and multi-level evaluation and guidance for energy conservation work [4]. It can provide comprehensive and multi-level evaluation and guidance for energy-saving work, and facilitate the implementation of subsequent energy-saving renovation, operation optimization, and energy-efficiency improvement work. Serra et al. [5] analyzed the energy use in public areas based on a machine learning system and hoped to seek a way to build a smart city through this model. To combine big data and machine language into an intelligent system for energy efficiency management of public buildings, Javanroodi et al. [6] used mathematical methods such as deep neural networks, R-language regression trees, and consequent forest simplification, respectively, to build a public building energy consumption prediction model for public buildings in the Croatian region. This model accurately predicts the data of various energy consumption indicators in public buildings and can be used as a basis for a substantial part of the smart city concept. Reindl and Palm [7] studied the influence of human activities in residential buildings on building energy consumption, giving the influence of indoor human activities on building energy consumption in terms of the use of household appliances, indoor temperature, and environmental quality. Shin et al. [8] studied the main factors of energy consumption in commercial buildings using a Gaussian regression algorithm and established a method for identifying building energy consumption using a combination of variables.

Therefore, to meet the development of the times and respond to the national call, the promotion and research of ultra-low, near-zero, and zero-energy buildings in China should be vigorously carried out to provide support and guidance for the medium and long-term building energy conservation work. Because of the large size of the earth and the wide distribution of various climatic regions, and the research on building energy-saving design should be tailored to local conditions, and it is economically and technically difficult to realize zero-energy buildings at this stage, so the building energy consumption should be gradually reduced, i.e., research should be conducted first for near-zero-energy buildings. Therefore, this paper only focuses on the energy-saving design of near-zero-energy residential buildings in the region, and analyzes the completed near-zero-energy demonstration buildings, aiming to provide theoretical and technical references for the development of near-zero-energy buildings in the region. In terms of the overall situation of energy consumption statistics at present, the data of energy consumption in public buildings in some places are crude, the management mode is confusing, and there is a lack of scientific energy use prediction and supervision, resulting in either inaccurate statistics or artificial fabrication in the obtained energy consumption data of public buildings, causing the government or institutions to face difficulties in carrying out energy-saving supervision work, especially the phenomenon of energy waste in medium and large public buildings. In particular, the phenomenon of energy waste in medium and large public buildings is serious. In response to this situation, by mastering data related to energy consumption in public buildings and establishing an analysis and prediction model for energy consumption in public buildings, the development trend of energy consumption in public buildings can be predicted promptly, which can aid and reference for decision-making related to building energy consumption.

2 COMPUTER-AIDED DESIGN EXPERIMENTS FOR BUILDING ENERGY EFFICIENCY IN THE CONCEPTUAL DESIGN PHASE

2.1 System Computer-aided Design for Energy Efficiency Simulation

Building energy monitoring system configuration also shows poor portability in engineering practice. The portability of electromechanical systems means that when the functional form of the building changes, the building system can operate normally without making many modifications. The reason for the poor portability of the current building energy consumption monitoring system is that the building energy consumption monitoring system based on the hierarchical centralized architecture sets energy consumption monitoring points to complete the system configuration based on specific building objects, but the scale, category, energy system and structure of different buildings are different, resulting in different system functions, energy consumption monitoring accuracy, monitoring points, and system integration methods for each building [9]. Under the hierarchical centralized architecture, the portability of the building energy consumption monitoring system is poor. To realize energy-saving control in buildings, the configuration engineer should fully grasp the variables that should be monitored at the point. Take the fan coil of the air conditioning system as an example, the parameters such as inlet water temperature, outlet water temperature, water flow rate, inlet air dry bulb temperature, and outlet air temperature of the fan coil should be monitored, so the configuration engineer is required to be highly professional. And with the continuous enrichment of intelligent buildings and green buildings, the various mechanical and electrical systems supporting the operation of buildings are expanding and diversified, accompanied by a large increase in the number of monitoring points of the building energy monitoring system, and the difficulty of system configuration is growing exponentially, as shown in Figure 1.

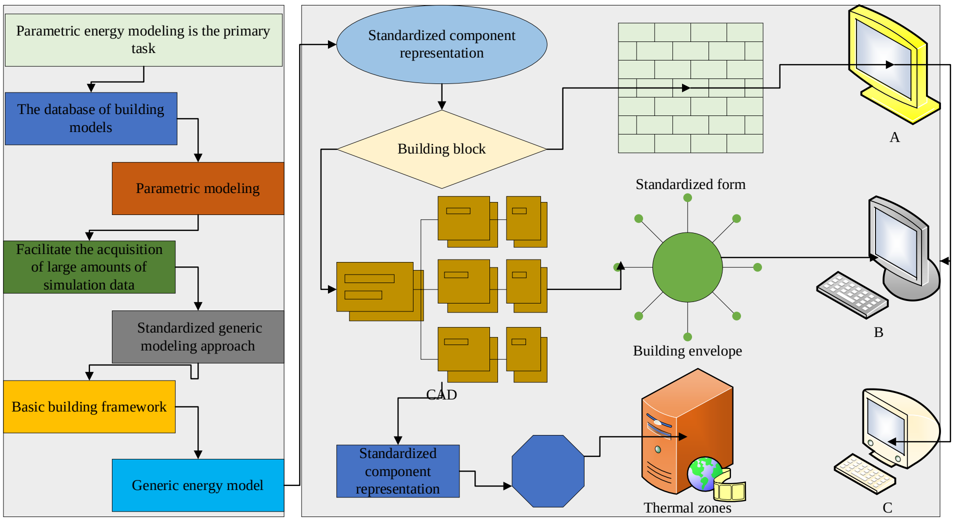

Figure 1: Computer-aided design framework.

Parametric energy modeling is the primary task of this study, intending to enrich the database of building models as much as possible to facilitate the acquisition of large amounts of simulation data. This parametric modeling is essentially the development of a standardized generic modeling approach, which results in a standardized model (also known as a reference model) that is converted from a basic building framework (generic energy model). This work is based on the basic principle of "standardized component representation" and a basic "building block" like a model. The standardized component representation is intended to provide a standardized form for defining the dimensions of the building envelope and individual thermal zones to further assign modeling rules to them. The so-called "building energy efficiency model" refers to the establishment of a mathematical model of building energy efficiency, and the concept of the mathematical model is: based on the observation of the research object, derived from the obtained phenomena and practical experience, and finally reduced to a set of mathematical expressions or specific algorithms reflecting the quantitative relationship of its internal factors, which are used to describe objective phenomena. Therefore, the energy efficiency model is to establish a set of mathematical expressions that can reflect the quantitative relationship of factors affecting energy efficiency changes and be applied to building energy efficiency.

After the model is established, it is only necessary to import the sub-measurement data of energy consumption of each power-using equipment and the online monitoring data of equipment directly into the model, and then the energy efficiency data of the building power-using equipment and the energy efficiency data of the building system can be obtained after calculation. Central air conditioning is a major energy consumer in public buildings. Some shopping malls and supermarkets not only use central air conditioning cooling mode for cooling in summer, but also use central air conditioning heating mode for heating in winter, so central air conditioning works for a long time a year, and it is necessary to evaluate its energy efficiency. After the renovation is completed, the energy efficiency is evaluated again until the evaluation reaches a satisfactory energy efficiency.

The proportion of energy consumption elasticity coefficient is closely related to various factors such as national economic structure, energy use efficiency, production techniques, management mode, and national living standard. Therefore, a lower energy consumption elasticity coefficient indicates a higher level of production technology and energy use efficiency, as shown in Figure 2.

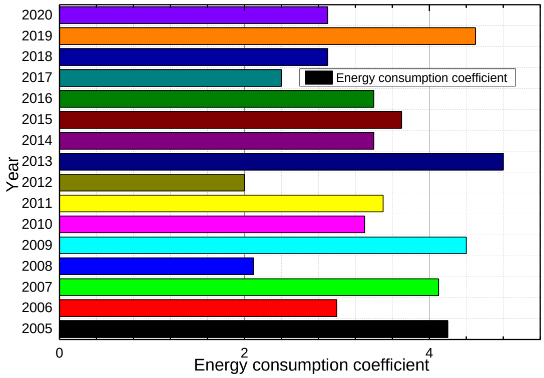

Figure 2: Year-to-year trend of energy consumption elasticity coefficient.

A targeted selection was made based on some structural issues to be addressed by the structural reform policy, and each driver selected was verified to have a strong correlation with public building energy consumption using a Pearson test. After identifying the macro drivers of public buildings under structural reform, each public building energy consumption driver is weighted. In multi-objective decision-making, the final weighting results vary because each type of decision-making method has its advantages and disadvantages. The hierarchical analysis method relies on expert experience to compare two factors for scoring, and the results are somewhat subjective. The entropy weighting method depends on the data itself and is an objective weighting method that is not subject to any subjective opinion. To address this problem, the use of a comprehensive weighting method to calculate the weights of the drivers of energy consumption in public buildings can well solve the problem of imbalance between subjective and objective decision-making methods. By using two methods simultaneously for weighting the drivers of energy consumption in public buildings, the comprehensive weighting coefficient α is determined to be 0.5 according to the results of the two decision-making methods, and finally, the comprehensive weighting calculation is carried out to obtain the comprehensive weights of each driver.

2.2 Experimental Design of Building Energy Efficiency Experiments

This characteristic is caused by those influences that have random characteristics and are not quantified. Therefore, to evaluate the random distribution of the standardized energy consumption ratio is to evaluate the random characteristics of the unquantified influences. Before starting the evaluation, the statistical characteristics of the stochastic distribution of the standardized building energy consumption should be clarified. The current mainstream energy consumption evaluation models lack stochasticity tests, and the default energy consumption ratio is equipped with sufficient stochasticity. The lack of this problem consideration is explained and improved in the following section.

The unique and complex correlation of influencing factors for building energy consumption brings resistance to building energy consumption comparison and evaluation on the one hand and provides technical ideas for splitting building energy consumption on the other hand. Since the correlation of building energy consumption to building service level, service volume, and local meteorological conditions is strong, a statistical regression model can be used to split the energy consumption into three parts based on the correlation of total building energy consumption and related parameters, energy consumption related to changes in meteorological parameters, energy consumption related to service increments and energy consumption of baseload independent of changes in meteorological parameters and services. The purpose of public buildings is to provide services for the corresponding functions and to provide the corresponding comfortable environment for this service. The maintenance of the environment depends on the elimination of the indoor environmental load of the building caused by the change of meteorological parameters; the functional service is to provide the corresponding space, equipment, and "service products" for each service recipient. The energy consumption of the building should be mainly for this functional service, and the energy consumption of meteorological parameters and service changes independent of the baseload is not related to the service provided by the building and does not belong to the energy consumption brought by satisfying the service requirements, so the smaller its proportion is, the better the energy utilization of the building. By classifying the building energy consumption according to this principle, the building classified energy consumption can be fully evaluated according to the proportion of each energy consumption and the sensitivity of energy consumption to each incremental parameter, and further point out the recommended measures for building energy saving, as shown in Figure 3.

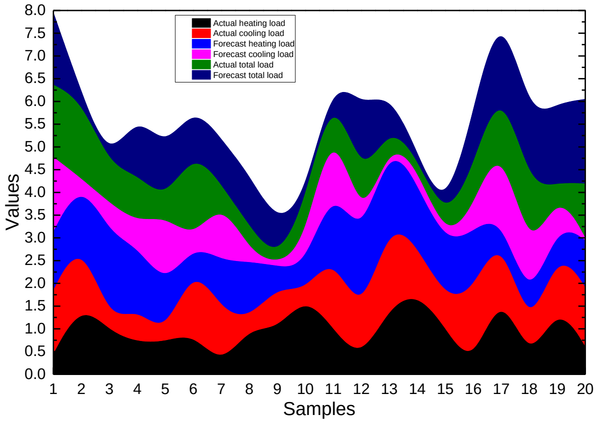

Figure 3: GA-BP prediction performance.

Figure 3 shows the energy consumption prediction model based on GA-BP, and the network structure and training sample size are determined by the "trial and error method", which greatly improves the applicability of the model. In conclusion, this method can quickly and accurately predict the heating and cooling energy consumption of buildings using simple design parameters and can evaluate the energy-efficient building design structures in conjunction with the corresponding standards. Finally, the feasibility and reliability of the method are verified by examples. A total of 12,500 office building models were built in the case study, and 70 hours of energy consumption simulation were experienced. Considering the computational volume and the difficulty of data collection, a network structure of 13-30-2 and a training sample size of 3200 were finally determined. The results of the case study showed that the method was able to accurately obtain predicted values of building energy consumption based on 13 design parameters in a relatively short period. This study greatly overcomes the current engineering application problems in this field, improves the speed of building modeling, enhances the efficiency of building energy consumption prediction, and improves the user environment. The method can also be applied to evaluate the energy performance of existing buildings and provide a basis for retrofitting decisions that require real-time feedback. Future research will focus on demonstrating the ability of the method to cope with more complex building profiles. As the energy model continues to be refined, the method will become a truly effective user-oriented energy prediction tool for green building design and retrofitting. The operation and management control parameters related to the building software conditions refer to the operation and control mode of the energy-consuming system when the building is in actual operation, including the setting of parameters and control strategies, etc. They also include parameters such as the indoor set temperature and humidity, the opening time of the lighting system, the operation mode of multiple chillers, and the maintenance status of the whole mechanical and electrical system. These parameters are easily affected by human factors, and users can also adjust them independently, reflecting the different operation and management levels of the building, which vary greatly among different buildings. Building owners and users can adjust operation strategies and change control parameters to improve the energy efficiency level of the building. The level of the building hardware system and the operation and maintenance level belong to the target of energy efficiency improvement, and the energy consumption level of the building can be improved and the energy efficiency of the building improved through energy-saving renovation or optimized operation; while the inherent operation parameters related to the first category of building services are restricted by the building function and operation characteristics, therefore, the influencing factors reflecting the content and service volume of the first category of building services should be selected as the standardized model of building energy consumption, as shown in Figure 4.

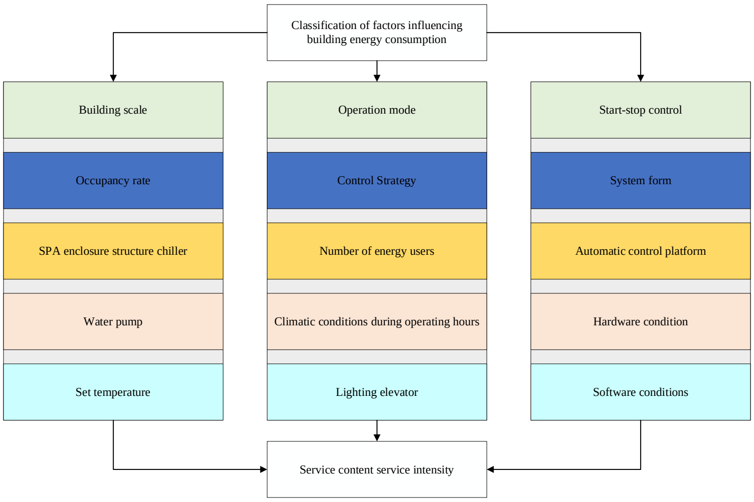

Figure 4: Classification of factors influencing building energy consumption.

The operation and management control parameters related to the building software conditions refer to the operation and control mode of the energy-consuming system when the building is in actual operation, including the setting of parameters and control strategies, etc. They also include parameters such as the indoor set temperature and humidity, the opening time of the lighting system, the operation mode of multiple chillers, and the maintenance status of the whole mechanical and electrical system [10]. These parameters are easily affected by human factors, and users can also adjust them independently, reflecting the different operation and management levels of the building, which vary greatly among different buildings, and building owners and users can improve the energy efficiency level of the building by adjusting the operation strategy and changing the control parameters. From the above analysis, it can be seen that the level of building hardware systems and operation and maintenance levels are targets for energy efficiency improvement, and the energy consumption level of buildings can be improved through energy-saving renovation or optimized operation to enhance building energy efficiency; while the inherent operation parameters related to building services in the first category are restricted by building functions and operation characteristics, so the influencing factors reflecting the content and service volume of building services in the first category should be selected as the modeling basis of the standardized model of building energy consumption. Similarly, the standardized modeling of building energy consumption does not consider the use of operational management control parameters related to building software conditions as standardized influencing factors, so there is room for improvement and renovation in terms of management and operation for buildings that have an abnormal energy consumption of the whole building due to low management level, energy-consuming systems in abnormal operation or not operating according to the optimal strategy. For example, high indoor set temperatures in winter or low indoor set temperatures in summer, fresh air units that do not operate according to optimized strategies, and excessive fresh air volumes in winter and summer can all result in high building energy consumption.

3 ANALYSIS OF RESULTS

3.1 Energy Efficiency Performance Results

The purpose of an energy efficiency assessment is first to identify the potential for energy savings in electrical equipment and then to evaluate the need for retrofitting. The following three examples are tests and analyses of the energy-saving potential of two air conditioning rooms and one chiller plant. The analysis of the examples shows that there is indeed wasted energy in some parts of the central air conditioning refrigeration system, cooling system, and chiller plant and that this wasted energy can be reduced through effective control measures. If only the extremely unreasonable parts of the control are optimized, the energy savings can be very significant. If the building energy efficiency assessment system model is used to optimize the system step by step, the energy-saving effect will be obvious. Figure 5 gives a record of the operation of air-conditioning equipment in a building during a period in the summer of a certain year. The data recorded in the figure is the same moment of every day, so the analysis is conducted utilizing horizontal comparison.

Figure 5 shows the graphs made from the collected data samples. A pair-by-pair analysis was applied to the valid data. Comparing day 1 and day 2, the load is relatively small, but the total current of the cooling pump supply and the temperature difference between the cooling water supply and return water do not change significantly, so there is room for energy saving; comparing day 3 and day 2, the load becomes smaller, but the cooling pump side provides more cooling capacity, so there is room for energy saving; comparing day 4 and day 5, the load is smaller, but the power of the cooling pump is higher, so there is room for energy saving. This is the result of too many units being turned on, so there is room for energy saving; on days 10 and 11, the load is relatively small, but the temperature difference between the cooling water supply and return water is relatively large, so there is room for energy saving; on days 14 and 13, the load is small, but the cooling capacity provided by the air conditioner is relatively large, so there is also room for energy saving. By changing the thickness of the roof insulation layer and thus the heat transfer coefficient in Design-Builder, the variation of heat consumption, cooling consumption and total energy consumption with the thickness of the insulation layer was obtained, and the trend is shown in Figure 6.

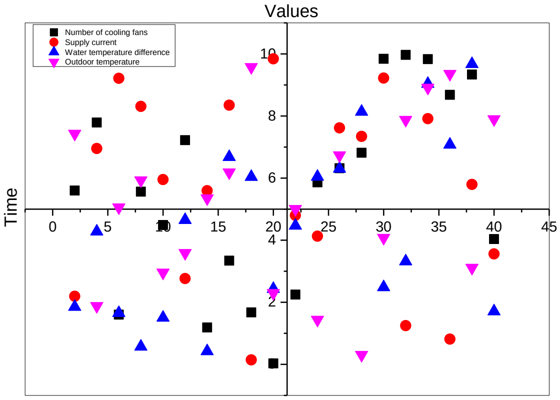

Figure 5: Results of sample collection.

From the figure, with the increase of the thickness of the insulation layer, the heat consumption of the building shows a slowly decreasing trend, but after the thickness of the insulation layer is more than 200mm, the curve tends to be stable. With the increase of the thickness of the insulation layer, the cold consumption of the building remains stable. In turn, the total energy consumption of the building also keeps a slowly decreasing trend first and then stays stable. Therefore, it is beneficial to increase the thickness of the roof insulation layer appropriately to reduce the total building energy consumption, but it is not advisable to increase the thickness of the insulation layer excessively, otherwise, it will affect the reliability and durability of its fixing, and it will increase the roof load and construction difficulty. Solar radiation has a great influence on building energy consumption. The building gets more solar radiation in winter, which can reduce the heat load in winter, but likewise gets more solar radiation in summer, which increases the cold load in summer.

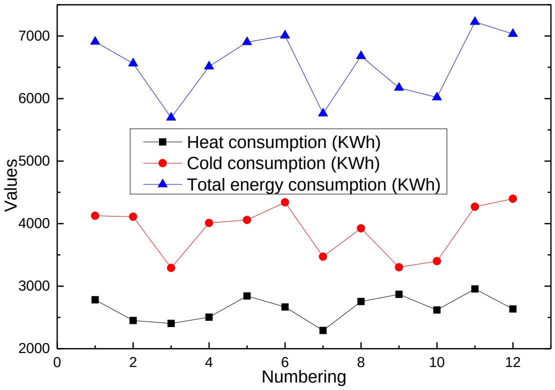

Figure 6: Variation of building heat consumption, cooling consumption, and total energy consumption with the thickness of roof insulation and the values.

3.2 Experimental Results

The statistical results of the energy consumption split model parameters for each sample are shown in Figure 7. The mean value of heating sensitivity for buildings with electricity-driven heat source is 0.234k, the mean value of heating sensitivity of electricity consumption for buildings with natural gas and municipal heat as a heat source is 0.123, and the mean value of heating sensitivity for a natural gas heat source is 0.067; the mean value of air conditioning sensitivity is

0.494; the temperature inflection points of heating and air conditioning are 16.01 and 20.90 °C, respectively; the baseload energy consumption is more discrete and related to the provision of service type and service volume.

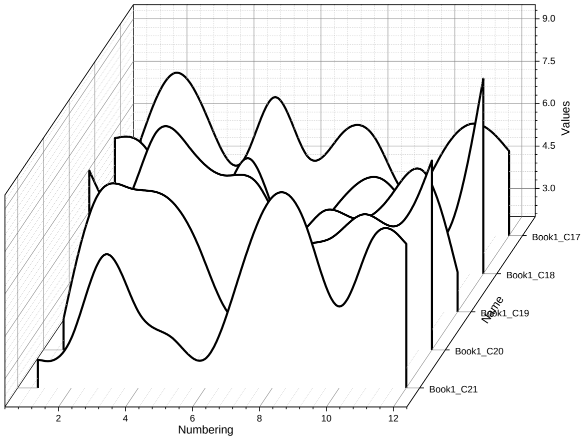

Figure 7: Statistical results of energy consumption splitting model parameters.

Considering the large number of design parameter combinations that need to be tested, the entire optimization solving process takes a considerable amount of running time. Most of the time is consumed in the EnergyPlus simulation process, which is about 3-5 minutes for each design scenario, and depending on the number of scenario trials selected for the study in question, the time consumption for EnergyPlus simulation alone can be about hundreds of years. Therefore, this study presents a basic research proposal for improving the overall efficiency of the optimization process. After using Design Builder to simulate the energy consumption of typical residential buildings in area and analyzing the influence of various factors on building energy consumption, it is concluded that: appropriately increasing the thickness of exterior wall insulation is beneficial to reducing building energy consumption, but when the thickness of exterior wall insulation increases to 200mm, i.e., the heat transfer coefficient of exterior wall reaches 0.16, the energy-saving effect is not obvious. The change of heat transfer coefficient has a small impact on building energy consumption, but appropriately increasing the thickness of roof insulation layer is conducive to reducing building energy consumption, however, when the thickness of exterior wall insulation layer increases to 200mm, i.e., the heat transfer coefficient of roof reaches 0.144, the energy-saving effect is not obvious; the design of building orientation should follow the principle of "north-south or close to north-south orientation is preferred. To meet the requirements of lighting, the ratio of south-facing windows to walls should be controlled between 0.4-0.5, and the ratio of north-facing windows to walls should be reduced as much as possible; the heat transfer coefficient of external windows should be minimized to reduce building energy consumption, and it is recommended to use energy-saving external windows to improve indoor comfort; the SHGC of south-facing external windows should be controlled between 0.5-0.7, and the SHGC of north-facing external windows should be reduced as much as possible. It should be reduced as much as possible, as shown in Figure 8.

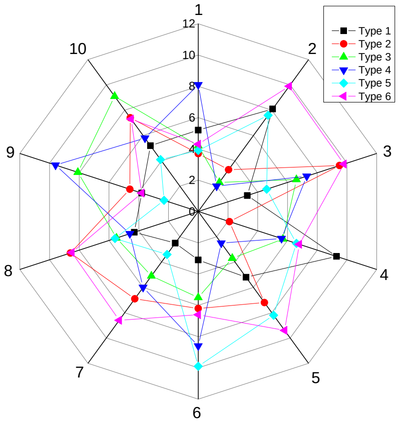

Figure 8: Building system load values.

Through the discussion of the energy planning of different subsystems of the actual project, the result of high energy consumption in the process of building operation and maintenance was obtained, and then through actual on-site research and analysis of actual data processing, the actual problems to be solved by the operation and maintenance framework system were proposed. The framework module of energy management, the framework module of the HVAC system, and the framework module of the BA system are discussed and studied separately, and the optimization framework of each module is proposed, which is combined with the subsequent pre-processing analysis of the actual project data and real-time feedback processing to achieve the engineering effect of solving actual problems. Management structure, comprehensive for mechanical and electrical operation and maintenance in the HVAC system, energy management system to provide realistic operation and maintenance optimization ideas, truly realize the integration of mechanical and electrical operation and maintenance management, intelligent and three-dimensional visualization, so that the building mechanical and electrical operation and maintenance towards a more intelligent place development.

4 CONCLUSION

Through a combination of the advantages of BIM technology and mechanical and electrical operation and maintenance framework technology, as well as field research and theoretical analysis of the structure and functional requirements of the HVAC subsystem and energy management subsystem, and form the basis of the actual problems of the project, combined with field research on-site data, the actual problems of the HVAC system, energy consumption control system, automatic control system and other parts of the HVAC system were analyzed, and the strategies and the practical application of the corresponding framework strategies were proposed to solve the problems of the project. It is applied research based on BIM system new mechanical and electrical operation and maintenance management and optimization transformation technology. Based on the statistical examination of the actual distribution characteristics of each parameter of the model, the quantification method of the energy consumption index of each group is proposed. The method of fitting the model follows the multi-level test multiple regression modeling method based on the OLS method proposed in this paper, and the actual data obtained from the research is used to establish and complete the grouped energy consumption comparison evaluation model based on the total energy consumption split for office buildings. This method solves the problem of no quantitative index for the evaluation of system grouping energy consumption due to the difficulty of obtaining data, realizes the horizontal comparison of building system grouping energy consumption, and provides a guarantee based on actual data for determining the target system for energy-saving renovation. The stability of the structure of the modeling method proposed in this paper is verified. To address the problem that the lack of testing of the scoring distribution causes the evaluation model to be inaccurate, a double testing method is proposed to ensure that the evaluation model conforms to the statistical distribution characteristics.

Qing Zhou, https://orcid.org/0000-0001-6354-5153
He Zhan, https://orcid.org/0000-0002-3610-7649
Gang Li, https://orcid.org/0000-0001-8613-5632

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