

Design and Implementation of an Intelligent Operation and Maintenance Management System for Near-Zero Energy Buildings

Zhankuan Shi^{1,*}, Mengyang Ma², Long Zhang³, Guowen Zhang², Wentao Qiao²

¹Hebei Bimu Construction Technology Co., Ltd, Shijiazhuang, Hebei province, 050051, China

²School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang, Hebei province, 050043, China

³School of Civil Engineering and Architecture, Hebei University of Engineering Science, Shijiazhuang, Hebei province, 050091, China

*Corresponding author: Mengyang Ma (Email: 15933477289@163.com)

Abstract

To address the issue of energy consumption and carbon emissions deviating from expectations due to improper operation and maintenance management in near-zero energy buildings, an intelligent operation and maintenance management system based on a B/S architecture was designed and developed. The system integrates active and passive collaborative management technologies to establish a multi-dimensional energy efficiency assessment system covering operational energy consumption, indoor environment, equipment efficiency, and carbon emissions. Based on real-time assessment data and energy consumption baselines, the system generates energy-saving and carbon-reduction strategies. Incorporating user behavior analysis, a closed-loop "assessment-diagnosis-control" management framework is constructed to significantly reduce carbon emissions during building operation. The system frontend uses Vue.js and Three.js to implement 3D building visualization and device status interaction. The backend, based on the Spring Boot framework, utilizes the WebSocket protocol for real-time data communication, enabling real-time diagnosis of building energy efficiency and energy-saving optimization, providing an effective solution for the refined operation and maintenance of near-zero energy buildings.

Keywords

Near-Zero Energy Building; Operation and Maintenance Management; WebGL; 3D Visualization.

1. INTRODUCTION

Energy consumption in the building sector accounts for approximately 40% of the world's total energy consumption and is one of the major sources of carbon emissions^[1]. Nearly zero-energy buildings, through passive design, active energy systems and the use of renewable energy, have minimized their dependence on external energy and have become an important direction for the development of building energy conservation^[2,3]. However, even if near-zero energy standards are achieved during the design phase, actual energy consumption often far exceeds design expectations during the operation phase due to factors such as equipment commissioning, user behavior, and management strategies^[4]. Traditional building operation and maintenance management relies heavily on manual inspections and annual energy efficiency audits, which have drawbacks such as slow data updates, delayed regulation, and

untimely fault response. With the development of the Internet of Things, big data, and Web3D visualization technology, building a data-driven, real-time interactive intelligent operation and maintenance platform has become a key path to improving building energy efficiency^[5]. Based on WebGL technology, this paper takes buildings in cold regions as an example, integrates building energy consumption analysis, equipment monitoring, and 3D visualization, and designs and implements an intelligent operation and maintenance management system for near-zero-energy buildings, aiming to achieve dual control targets of energy consumption and carbon emissions during the building operation phase.

2. OVERALL SYSTEM DESIGN

2.1. System Architecture

Based on the requirements of a near-zero energy building operation and maintenance system, this system adopts a client-server architecture with a front-end and back-end separation. The overall platform architecture was designed based on the platform's design goals and principles, as shown in Figure 1.

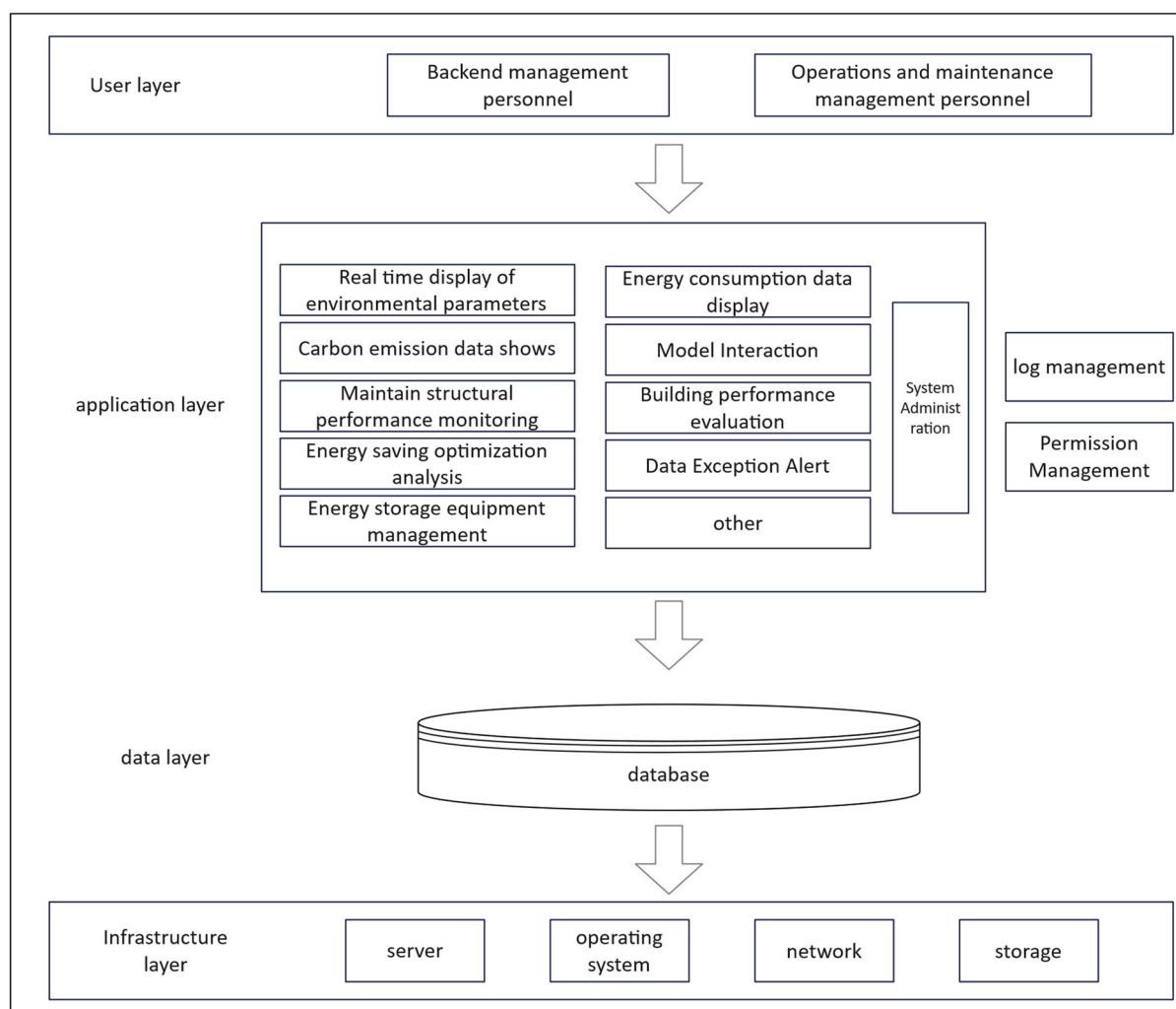


Figure 1. Overall framework diagram of the platform

2.2. Technical Architecture

The overall technical architecture of the operation and maintenance platform adopts a front-end and back-end separation design pattern. The front-end is responsible for user interaction and data visualization, while the back-end is responsible for data processing, business logic execution, and database interaction.

The front-end implements various user interfaces using data binding and a component-based development model provided by Vue2. Leveraging the Three.js library in WebGL, the building and its equipment are displayed as 3D models. Users can click, rotate, and zoom to observe various building data and status in real time. WebSockets are used for real-time communication with the back-end, enabling instant data push and updates. In the event of equipment failure or energy consumption exceeding a preset range, the back-end pushes alarm information to the front-end via WebSockets, and the user interface is immediately updated to display the latest data. For data that requires regular review, the front-end uses a polling mechanism to request the latest data updates from the back-end. The backend, built with a microservices architecture using Spring Boot, features a flexible, modular design. It handles business logic including building equipment status management, energy data statistics and calculations, and real-time fault monitoring and alerting. There are two primary communication methods between the backend and frontend: WebSocket enables the backend to push relevant information to the frontend interface in real-time upon changes in building equipment status; a RESTful API is used to periodically query non-real-time data. The backend system provides strict authentication and permission control mechanisms to ensure platform data security. The database layer uses MySQL as a relational database, enabling efficient processing of large-scale building operations and maintenance data and supporting high-concurrency queries.

3. SYSTEM CORE FUNCTIONS AND INNOVATION IMPLEMENTATION

3.1. Active-Passive Collaborative Management System

The system has established a collaborative control mechanism combining active and passive technologies to conduct real-time monitoring and dynamic warning of the operating parameters (such as COP, power generation, and air volume) of equipment such as fresh air systems, ground source heat pumps, and photovoltaic power generation to ensure continuous and efficient operation of the equipment. By deploying temperature and humidity sensors on the enclosure structure, the thermal performance and natural ventilation potential are monitored in real time, abnormal thermal bridges or airtightness problems are identified, and ineffective energy consumption is minimized.

3.2. Near-zero energy building operation and maintenance performance evaluation

In order to ensure that buildings can continue to meet the requirements of near-zero energy standards during operation and maintenance and maintain a balance between energy consumption and renewable energy production, a systematic operation and maintenance evaluation mechanism needs to be established. This study is based on the "Near-zero Energy Building Technical Standard" GB/T 51350-2019^[6] and based on the differences in the sensitivity of indicators to building energy efficiency, the evaluation parameters are divided into two categories: key constraint indicators and auxiliary indicators, and a hierarchical control model is constructed to achieve closed-loop management of accurate energy efficiency monitoring and optimized regulation.

3.2.1. Key Constraints

Key constraints are the core parameters that determine the building energy efficiency level and are directly related to the building's energy consumption and indoor comfort. For near-zero

energy buildings, energy efficiency optimization generally depends on key constraints. Therefore, the rational selection of key constraints is of vital importance to ensure that the building meets the zero energy standard. The key constraints are shown in Table 1.

Table 1. Key constraint indicators

Indicator name	Selection criteria
Overall air tightness of building	It directly affects the heat loss and heat gain of buildings, and is crucial for reducing indoor and outdoor heat exchange and controlling indoor temperature fluctuations
Performance of the Fresh Air Heat Recovery Unit	Good performance of a fresh air heat recovery unit can not only improve air quality, but also significantly reduce energy consumption for heating and ventilation while ensuring indoor comfort
Environmental control integrated machine performance	The performance of the integrated environmental control machine integrates multiple control factors such as indoor temperature and humidity, air quality, etc., ensuring maximum building energy efficiency while maintaining the indoor environment.
Building energy consumption	Building energy consumption directly reflects the energy efficiency of buildings in actual operation and is the basic indicator for evaluating energy efficiency.
Indoor temperature and humidity	Indoor temperature and humidity directly affect the thermal comfort of buildings, which in turn affects energy consumption and indoor environmental quality.
Inner surface temperature of thermal bridge Inner surface temperature of thermal bridge	Excessively high or low temperatures on the inner surface of thermal bridges can lead to energy wastage and reduced indoor comfort
Fresh air volume	Too low a ventilation rate can lead to poor air quality, while too high a rate can result in additional energy consumption.

Based on the evaluation results and according to different situations, targeted optimization suggestions and measures are proposed. Some of the content is shown in Table 2, which provides the operation and maintenance platform with standards and basis for managing building performance.

3.2.2. Auxiliary indicators

Auxiliary indicators reflect the derivative influencing factors of building operation. Their optimization can improve the overall performance of the system, but they cannot determine the energy efficiency level alone. In the near-zero energy operation and maintenance management system, the "monitoring-warning-suggestion" non-mandatory intervention model is followed. Auxiliary indicators are shown in Table 3.

Table 2. Key constraint indicator optimization strategy

Unmet Indicators	Optimization strategy
Overall air tightness of the building	Improve building structure or make airtight modifications
Performance of the Fresh Air Heat Recovery Unit	Clean the heat exchange core, check the lubrication of the fan bearings, and calibrate the temperature and humidity sensors
Building energy consumption	Compare real-time energy consumption data with historical baselines to identify high-energy consumption areas or equipment and make timely adjustments
Indoor temperature and humidity	Improve the building's air conditioning and ventilation systems to optimize indoor temperature and humidity; use high-efficiency insulation materials to reduce the impact of external climate change on the indoor environment
Inner surface temperature of thermal bridge	Improve the insulation of the building facade, use more efficient insulation materials, or adopt hollow walls
Fresh air volume	Adjust the operating air volume of the fresh air system, repair or replace the fresh air unit

Auxiliary indicators also have a significant impact on the building's comfort, air quality, and overall operating efficiency, but they do not directly determine whether the building meets the near-zero energy consumption standard. The intelligent operation and maintenance management platform can improve related performance by adjusting and optimizing building energy consumption. The optimization strategy is shown in Table 4.

Table 3. Auxiliary indicators

Auxiliary indicator name	Selection basis
Indoor PM2.5 concentration	Indoor PM2.5 concentration is greatly affected by the outdoor environment, but design, construction and energy-saving measures cannot completely control its concentration. Therefore, although indoor PM2.5 concentration is a necessary test item in operation evaluation, it cannot be used as the basis for whether a building meets the near-zero energy consumption standard.
CO ₂ concentration	Although CO ₂ concentration has an impact on indoor air quality and is affected by the outdoor environment and indoor human activities, its concentration control does not rely entirely on design and energy-saving measures. Therefore, CO ₂ concentration should be a necessary test item for operation evaluation, but it cannot determine whether a building meets the near-zero energy consumption standard.
Heat transfer coefficient of non-transparent envelope structure	The heat transfer coefficient limit of non-transparent envelope structures can be adjusted according to other energy-saving design requirements. Therefore, the average heat transfer coefficient of the exterior wall and roof is also set as an auxiliary indicator.

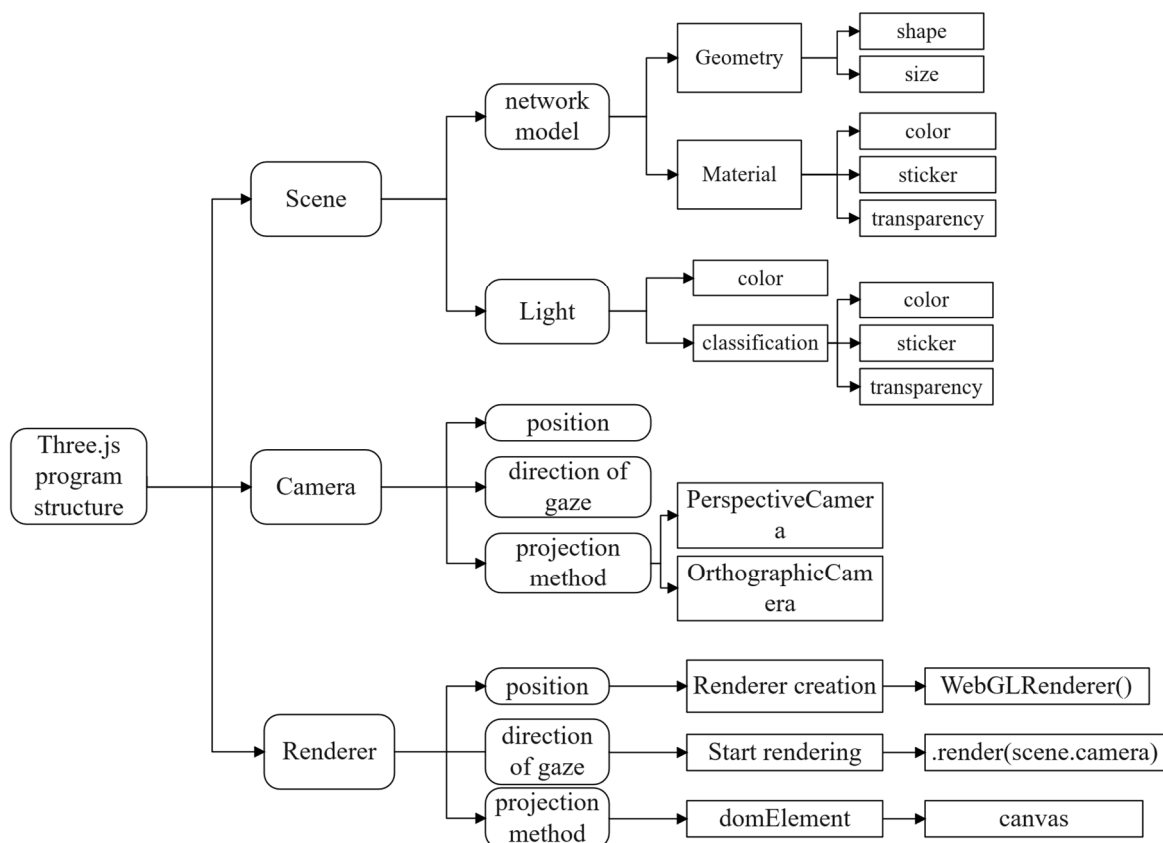
Table 4. Auxiliary indicator judgment criteria and optimization strategies

Unmet Indicators	Optimization strategy
Indoor PM2.5 concentration CO ₂ concentration	Increase fresh air volume or use air purification equipment
Heat transfer coefficient of enclosure structure	Exterior wall and roof renovation or thermal bridge blocking at key nodes

3.3. 3D Visualization and Interaction

To monitor the visual status of a near-zero-energy building's 3D model, it's necessary to first establish a 3D visualization model of the building. Then, all data from the building's operation must be collected, processed, and stored. This data is connected to the server database in real time via WebSocket technology, enabling real-time status mapping and interaction.

Three.js, a powerful 3D graphics library, can build complete 3D interfaces using three fundamental components: scenes, cameras, and renderers. Using these elements for design and rendering allows developers to create a rich variety of 3D visual effects. The Three.js program structure is shown in Figure 2.

**Figure 2.** Three.js program structure diagram

There are two main ways to use Three.js to display 3D models: internal object creation and external model import. Since the building model is relatively complex and the model drawing process of Three.js is cumbersome, it is necessary to use professional 3D modeling software to build the model and then import it into the scene.

(1) 3D scene initialization: In the `init()` method, the basic elements of Three.js are first initialized, including the renderer, camera and light source. The renderer is configured to enable shadow mapping to ensure the authenticity of the lighting effect. The camera uses perspective projection and sets the appropriate viewing angle and zoom level to ensure that users can clearly view the building and its components. Some relevant codes are as follows:

(2) Model loading: After the model is completed in 3DMax software, it is exported to GLTF format using the Babylon export plug-in, and then loaded and rendered through the `GLTFLoader` of Three.js. Three.js parses the geometric information, materials, and textures of the model in the imported GLTF file and renders and displays it on the browser side, ensuring good interactivity and visualization effects.

(3) 3D scene update: In the `renderScene()` method, the platform uses `requestAnimationFrame()` for continuous rendering to ensure the smoothness of the 3D scene. At the same time, `OrbitControls` allows users to rotate, zoom, and move the camera to view the building model from different angles.

(4) After building the model scene and importing the model, it is necessary to realize scene roaming and interact with the model, display the operating status of the equipment in the model, and control the model. In order to better interact with the three-dimensional model, the raycasting method provided by Three.js was selected. Each sub-model in the model was traversed in the system, and the specific components were marked using the `userData` attribute. Each sub-model can be recognized by the user after clicking and the corresponding interaction logic is triggered. When the user clicks on the three-dimensional model, the mouse event is converted into Three.js standardized device coordinates, and the raycaster is used to detect whether it intersects with the objects in the model. If there is an intersection, Three.js will detect the device click through the event and then call `Vue2` to update the detailed information of the device operating status to ensure that the user can see the operating data of each device in real time.

3.4. Energy-Saving Optimization and Closed-Loop Control

Given the characteristics of near-zero-energy buildings, energy-saving optimization strategies within the operation and maintenance system involve multiple aspects, including technical means, design optimization, management measures, and institutional safeguards. By comprehensively collecting and analyzing building energy consumption data, the intelligent operation and maintenance platform can conduct in-depth data analysis, identify energy efficiency issues within the building, and provide targeted energy-saving optimization recommendations.

For residential buildings in cold regions, establishing a representative energy consumption baseline is necessary to accurately understand the building's actual energy consumption levels during both heating and non-heating periods. To ensure the accuracy of baseline data and reflect the building's energy consumption patterns under different outdoor temperature conditions, the management system uses a four-week data collection plan, encompassing the two core operating phases of winter heating and summer cooling, to capture the building's energy usage characteristics under different climatic conditions. To ensure the accuracy and relevance of baseline data, historical data must first be matched to predefined time periods, such as daily routines, quiet rest periods, weekends, and holidays, and energy consumption values calculated for each time period.

The average energy consumption $E_{avg,t}$ for a given time period t can be expressed using the following formula:

$$E_{avg,t} = \frac{1}{n} \sum_{i=1}^n E_{i,t} \quad (1)$$

Where: $E_{avg,t}$ —the average energy consumption for time period t ;

$E_{i,t}$ —the energy consumption value of the i -th data point in time period t ;

n —the total number of data points in the time period.

If resident behavior in a residential building exhibits significant seasonal fluctuations, conventional static baselines may not fully capture changes in resident energy usage patterns. Rolling window technology can be used to dynamically update the baseline, ensuring that it adapts to changes in resident energy usage habits over time. In this rolling window application, the current time window is T_w , and historical energy consumption data $E_{roll}(t)$ can be updated for each time period. The specific formula is as follows:

$$E_{roll}(t) = \frac{1}{n_w} \sum_{i=1}^{n_w} E_{i,t} \quad (2)$$

Where: $E_{roll}(t)$ —the energy consumption for the rolling window period T_w ;

n_w —the total number of data points in the 7-day window.

Using rolling window technology, baselines can be adjusted and optimized in real time without having to reset the entire baseline, improving the accuracy of energy consumption analysis. The monitoring system compares the real-time energy consumption $E_{current,t}$ during the current time period with the corresponding baseline value $E_{avg,t}$. When the deviation exceeds the preset threshold ΔE , it automatically triggers an alarm or prompt message to prompt the householder or management staff to check whether the energy consumption is abnormal. The abnormal deviation formula is as follows:

$$\Delta E = |E_{current,t} - E_{avg,t}| \quad (3)$$

After identifying energy usage anomalies, the intelligent operation and maintenance platform generates energy-saving optimization recommendations based on the type of anomaly. For example, for nighttime air conditioning strategies, the system can automatically adjust air conditioning operation during off-peak hours, reducing the number of active air conditioners or lowering operating power to retain only the minimum required power for temperature control. Meanwhile, lighting circuit control strategies can adjust light brightness based on real-time lighting conditions and implement time-sharing lighting by floor or room, reducing power consumption while fully utilizing natural light.

Based on historical energy consumption data and real-time monitoring information, the system establishes an energy consumption baseline and identifies energy usage anomalies (such as air conditioner idling and redundant lighting). Integrating external meteorological data and user behavior patterns, it generates energy-saving strategies, including time-sharing equipment scheduling and power adjustment, forming a closed-loop management mechanism of "monitoring-evaluation-control-feedback."

4. SYSTEM CORE APPLICATIONS

After system development is complete, the main functional interfaces will include energy audit, performance evaluation, fresh air system, ground-source heat pump system, energy storage system, photovoltaic and wind power system, and energy-saving optimization system. The homepage interface is shown in Figure 3.



Figure 3. Three.js program structure diagram

The main function of the energy consumption monitoring system is to continuously record electricity and natural gas consumption and carbon emissions and store them in a database. By analyzing these energy consumption data, it helps managers better understand energy consumption and effectively formulate energy-saving plans; the building performance evaluation module mainly integrates the data of various monitoring devices and compares them with the established standards to promptly detect abnormal behavior during building operation and provide a data basis for energy-saving optimization; in terms of fresh air unit management, the system can display equipment operating parameters in real time and issue alarms in time when abnormalities occur to ensure that the air purification equipment is always in an efficient working state; the ground source heat pump system focuses on the continuous monitoring and status maintenance of equipment operating parameters. This system mainly ensures the smooth operation of the entire heat exchange system by collecting key indicator data such as water temperature, refrigerant pressure and water flow on the ground source side and user side of the unit in real time; the core function of the energy storage system is to store electricity generated by clean energy such as solar energy and wind energy, and release it for use during peak hours. The operation and maintenance platform continuously monitors the charge and discharge status of the battery pack, and combines this with the building's actual electricity demand to ensure the efficient operation of the energy storage system and the rational scheduling of resources. During daily operation, solar and wind energy systems require real-time monitoring of current, voltage, and power, and timely feedback on power generation and consumption status, facilitating analysis and optimization of energy efficiency. The core function of the energy-saving optimization system is to optimize the building's energy efficiency through data analysis and energy-saving strategies, and to timely adjust the equipment's operating strategy based on historical energy consumption trends to provide users with personalized energy-saving solutions to achieve optimal energy management results.

5. CONCLUSION

To address the energy efficiency deviations that often occur during the operation of near-zero-energy buildings, this paper designed and implemented an intelligent operation and maintenance management system based on a B/S architecture. By integrating IoT monitoring, big data analysis, and WebGL 3D visualization technology, this system creates a comprehensive management platform that integrates data monitoring, energy efficiency assessment, fault

warning, and energy-saving optimization, providing a scalable solution for the operation and maintenance of near-zero-energy buildings.

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