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Design and Management of a Spatial Database for Monitoring Building Comfort and Safety

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Abstract: As the impacts of climate change on urban environments and buildings become more and more prominent, building comfort and structural safety monitoring becomes crucial. However, efficiently storing and managing the multi-source monitoring data generated during the long-term monitoring process has been an urgent challenge. In order to solve the above problems, this paper designs and develops a spatial database management system for building comfort and structural safety monitoring based on standard database development tools. A conceptual model of a spatial database for building comfort and structural safety monitoring is proposed, and the entities, attributes, and connections in the model are discussed to transform the E-R conceptual model into a logical model supported by an object-relational spatial database management system. Based on this conceptual and logical model, a mainstream backend framework was adopted and combined with common database and programming language tools and BIM (Building Information Modeling) technology for development to establish a spatial database management system with data storage, management, analysis, and visualization functions. We designed building monitoring experiments and proved through the experiments that the database management system can stably store, analyze, and manage the monitoring data and visualize the display, with the advantages of a fast response speed and low error rate. The spatial database system improves the storage and management efficiency of building comfort and structural safety monitoring data, eliminates redundant data, and realizes comprehensive analysis and management of building comfort and structural safety monitoring data. It provides data support for building comfort and structural safety assessment, helps users analyze the formation mechanism and evolution law of the urban heat island effect, assesses the interrelationship between climate change and urban building morphology, and constructs an urban thermal environment that is more adaptable to climate change.

Keywords: spatial database; building monitoring; building comfort; structural safety

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1. Introduction

With the developments of data science and big data [1], urban lifelines have paid more attention to addressing climate change [2,3]. As an essential component of urban lifelines, building comfort and structural safety monitoring plays an important role in analyzing the impact of climate change on urban environments and buildings [4]. Building comfort can help to analyze the formation mechanism and evolution of the urban heat island effect. For example, most buildings in a city suffer from indoor overheating. In that case, these buildings are absorbing and storing a large amount of solar radiation, which increases the temperature around them and exacerbates the urban heat island effect. The monitoring of structural safety can be used to assess the relationship between urban building morphology and climate change; for example, strong winds may cause risks to buildings, and building collapse results in changes in building morphology, which affects changes in the wind field, which leads to changes in the climate [5–8]. However, long-term monitoring activities are bound to produce a complicated type of monitoring data [9–11], such as point cloud data, BIM [12], strain values, temperature and humidity values, and the tilt angle. How to effectively store and manage these monitoring data is a prerequisite for improving the efficiency of urban thermal environment management and maximizing its value for building monitoring [13,14]. Therefore, it is necessary to develop a spatial database system for monitoring building comfort and structural safety to improve the efficiency of monitoring data storage and management and to realize comprehensive analysis and management of building comfort and structural safety monitoring data. The system can help to analyze the formation mechanism and evolution of the urban heat island effect, assess the interrelationship between climate change and urban building form, promote the improvement of urban quality of life, mitigate the challenges posed by climate change, promote sustainable urban development, and build a more climate-resilient urban thermal environment.

1.1. Literature Review

In building monitoring, the methods of handling the large amount of monitoring data generated by long-term monitoring can be divided into the following main categories. Some researchers rely mainly on traditional data recording and analysis methods, which do not involve the study and use of databases; this type of research has limited storage and management of data, a large amount of data is stacked together, and lacks systematic data processing and querying capabilities, and is only applicable to the monitoring of a limited and more straightforward scale. Xue J et al. [15] proposed a method to monitor the construction process of a high-rise building by identifying the unfinished building components from a top view through the target detection technique, comparing and registering them with the BIM components, and inferring the overall construction progress by counting the number of identified and registered components. Li X et al. [16] designed a structural health monitoring system to monitor the overall condition of the South Building of East China Hospital and the condition of critical components to ensure structural safety during the overall lifting of the South Building of East China Hospital by 1.30 m to correct the settlement. Guo M et al. [17] used UAV images and ground-based LiDAR point clouds for sweep detection of wooden towers and performed multi-period data comparisons to realize high-precision deformation monitoring of wooden towers. However, the paper did not deal with the data storage problem, and there was no database storage.

Some researchers have begun to utilize database technology to store data. However, these databases tend to be limited in size and have a single data storage content, which needs to be improved to respond to complex and diverse monitoring needs. Arslan M et al. [18] developed a "real-time environmental monitoring, visualization, and notification system" using sensor technology integrated with BIM to monitor temperature and humidity sensor data in real-time to ensure worker health and safety in hot and humid environments. An SQL Server database was constructed, but there were only six data tables for building and room identification, sensor information, and threshold-triggered notification history. Valinejadshoubi M et al. [19], developing an Internet of Things (IoT) and BIM-based automatic alarm system for thermal comfort monitoring of buildings, successfully developed a relational database system using MySQL for storing and updating the data collected by the sensors and associated sensor parameters. However, the database system contains only six data tables and is relatively small. Meng Q et al. [20] developed an Internet of Things (IoT)-based sensing system for building vibration monitoring, in which a MySQL database was constructed for long-term data storage, mainly focusing on all the raw data from acceleration sensors, processed data, and analyzed results, with a relatively homogeneous storage content.

Many researchers have begun to build more complex monitoring databases for efficient storage and management of monitoring data to accomplish more complex monitoring needs. However, such databases do not have the function of spatial characterization or correlation, limiting their application's scope in building monitoring. Liu T et al. [21] designed a structural health monitoring (SHM) system using a variety of sensors to monitor different structural parameters that significantly affected the safety of the structure and established a database system to manage the monitoring data from nearly 600 sensors and developed structural monitoring, analysis, and evaluation software in conjunction with finite element software, which realizes the exchange of data and comparison of the results between on-site monitoring and numerical modeling, to evaluate the performance of the structure during construction. Liu G et al. [22] proposed an information physical system (CPS)-based real-time monitoring and visualization method of greenhouse gas emissions from assembled buildings for real-time monitoring research of greenhouse gas emissions. They use MySQL to receive and store emissions data from remote servers and all kinds of related data. Yuan, S. et al. [23] designed and implemented the mentioned remote wireless sensor network-based foundation settlement dynamic early warning system for high-rise buildings with lower computer hardware and software and an upper computer system to monitor the foundation settlement of high-rise buildings and constructed a SQL Server database to store all the monitoring data, which ensured the effective management of the foundation settlement detection data of high-rise buildings. Yang Q et al. [24] designed and implemented a structural health management system for wood-framed ancient buildings, deploying 104 sensors of six different types to monitor environmental effects and structural responses and storing a large amount of data collected by the sensors and maintenance information in a SQL Server database to realize the structural health monitoring of the Feiyun Wooden Pavilion in China. Xu J et al. [25] designed a conceptual model combining Building Information Modeling (BIM) and real-scene 3D models to effectively manage sensors and their corresponding monitoring data for structural health monitoring to ensure building safety. Moreover, the monitoring data of multiple sensors are stored in a database management system.

Regarding database technology, the demand for the corresponding databases, which support storing big data, is increasing with the continuous accumulation and rapid growth of data. Denton et al. [26] discussed the advantages and disadvantages of commercial enterprise software and personal databases, such as Oracle, IBM's DB2, Microsoft Access, PostgreSQL, and MySQL. Bravo et al. [27] designed a document management system by applying MySQL and Apache2 Server to storage, control, management, and distribution. Peng et al. [28] analyzed the functional requirements of college dormitories and designed a student dormitory management system using Java, SSM framework, and MySQL. Eyada M et al. [29] evaluated the performance of two types of databases, MongoDB and MySQL, in cloud computing to handle different specifications of resources. MongoDB outperforms MySQL in terms of latency and database size and is more resource-efficient, and MySQL needs high-performance resources to work at a lower performance. Gyoroedi C et al. [30] proposed methods to optimize database structure and queries and comparatively analyzed the impact of the optimization methods on each specific DBMS when performing CRUD (Create, Read, Update, Delete) requests. Zmaranda D et al. [31] compared two popular open-source DBMS: relational MySQL and non-relational Elasticsearch. They proposed and implemented a data replication solution that imports data from the predominantly relational MySQL databases into Elasticsearch, which a MySQL document stores as a possible alternative for a more efficient data search. Yin P et al. [32] developed a software system for an urban land planning database in Shanghai, China, based on MySQL; They established a platform with functions of data management, information sharing, and map assistance to realize efficient storage and management of land data.

1.2. Research Methodology

In China, most data generated from building monitoring has begun to be stored and managed using database technology. However, more research must be conducted on storing and managing multi-source data generated in building comfort and structural safety monitoring, especially on storing and managing spatial data such as 3D point clouds and BIM models. There is no spatial database specialized for building comfort and structural safety monitoring. At the same time, there are abundant database technologies to develop building comfort and structural safety monitoring databases. Moreover, a complete data management platform should contain primary data and a complete and practical database management system.

Therefore, in order to be able to efficiently store and manage the multi-source data generated in building comfort and structural safety monitoring, data support is provided for the study of the interrelationship between climate change and building comfort and structural safety. We propose an object-relational spatial database, design the conceptual and logical models of the spatial database for building comfort and structural safety monitoring, and discuss the entities, attributes, and connections in the model. Based on the conceptual and logical model, a spatial database management system with the functions of data storage, management, analysis, and visualization is established by adopting a mainstream backend framework and combining common database and programming language tools and BIM technology for development. The method for designing a spatial database is discussed in detail, and the main functional modules are described. In addition, integrating BIM technology into the spatial database management system enhances the monitoring data's application value and the real-time nature of the condition information. It helps the in-depth analysis and efficient management of building comfort and structural safety monitoring data and further promotes the development and application of building monitoring technology.

The contributions of this study are the following: (1) The conceptual model and logical model of the spatial database for building comfort and structural safety monitoring are proposed, and the object-relational spatial database for building comfort and structural safety monitoring is designed, which is targeted to solve the problem of storing and managing the massive monitoring data generated in the process of building comfort and structural safety monitoring. (2) BIM technology is integrated into the spatial database management system, and the management and visualization functions of BIM-based building monitoring data are designed and implemented to achieve a high degree of visualization and interaction of monitoring data on the website, which promotes the application and development of building monitoring technology.

2. Design of the Spatial Database

2.1. Requirements Analysis of Spatial Database

The first step in designing a monitoring database is to conduct a requirements analysis, which involves a detailed investigation of the monitoring system's applications and working environment, identifying the various needs of the users and thus determining the functional requirements. The core objective of the design of this monitoring database system is to store and manage multi-source data generated from building comfort and structural safety monitoring, especially spatial data such as 3D point clouds and BIM models. It critically supports urban climate resilience studies and helps to better understand the interrelationships between climate change and building comfort and structural safety. Based on the results of literature research and expert consultation, the basic requirements of the building comfort and structural safety monitoring database are the following:

The building is used as the monitoring object, including ID, name, location, and remarks, and several sensors are installed in each monitoring object. The sensors include the sensor ID number, the monitoring object ID number, the installation location, the installation time, the sampling period, the two-level warning thresholds, and remarks. Each sensor has a designated monitoring data entity for storing specific monitoring values collected by the sensor; for example, LIDAR acquisition data contain the acquisition time, 3D point cloud data, color information, and reflection intensity. A sensor can trigger multiple warning events, which should record the time of occurrence, the sensor number, the trigger level, the trigger monitoring value, and the processing work. At the same time, associate each monitoring object with a BIM model; the essential attributes of the BIM model include the model ID, name, creation time, last update time, and the path to the model file; the BIM model is dynamically associated with the monitoring objects and sensors that are able to be added, modified, or deleted with changes in demand. In the BIM model, the location and status of the sensors need to be represented, such as sensor installation location, online status, last sampling time, and latest readings, and each BIM model also has the corresponding component-related data and other format data. Finally, each monitoring object is associated with a set of typical defect documents that categorize typical defects and provide corresponding data for each categorized typical defect.

In contrast to conventional databases, this database focuses on meeting the specific needs of building comfort and structural safety monitoring, especially the storage and management of BIM and point cloud data. It has a complex data association structure while supporting multi-source data integration and dynamic association. The database improves the efficiency of urban building monitoring and provides essential data support for climate change research and sustainable urban development.

2.2. Design of Conceptual Model

The conceptual structure is a critical step in the entire database design process. Conceptual structure design uses abstraction mechanisms to organize the data obtained in the stage of requirements analysis. The entities, the related attributes of entities, and the connections between entities are formed [33]. The database's entities, attributes, and connections in this paper are discussed as follows.

In the spatial database for building comfort and structural safety monitoring are entities, monitor objects, sensors, LiDAR, LiDAR data, BIM models, typical defects, static monitoring data, etc. Attributes are characteristics of the entities, and an entity can be described by several attributes. For example, the attributes of the monitoring object entity include ID, name, location, and notes; the attributes of the sensor entity include ID, installation location, installation time, warning threshold, danger threshold, sampling period, usage environment, and notes; the attributes of the LIDAR entity include sensor ID, operating frequency, maximum detection distance, accuracy, resolution, and field-of-view angle; the attributes of the LIDAR data entity include time, 3D point coordinates, color information, reflection intensity; the attributes of BIM model entities include model name, creation time, modification time, model file path, model label, model status; the attributes of typical defect entities include defect type, location, discovery time, severity, and repair status; the attributes of static monitoring data entities include acquisition time, temperature, humidity, wind speed, wind direction, PM2.5, and noise. Separate E-R models are created based on each entity and its attributes. The attributes of each local E-R model must end with data items, i.e., they cannot be subdivided into sub-attributes, and they cannot have links with other entities. The links can only occur between entities. The E-R conceptual model for the spatial database for building comfort and structural safety monitoring is shown in Figure 1.

2.3. Design of Logical Model

Based on the conceptual structure, the logical structure of the database is designed to convert the E-R diagram of the entity class to be consistent with the data model of the spatial database. When converting the conceptual structure to the logical structure, the relationship between entities should be transformed into the corresponding model [34]. This paper proposes a hierarchical logical structure to design the database tables based on the relationships between the entities of the E-R conceptual model of the spatial database for building comfort and structural safety monitoring. A primary key is defined for each entity in order to set the primary attribute as a non-null value, and the corresponding foreign key should also be defined. The ID of the monitoring object, serving as a unique identifier, should be used as a foreign key in the sensor entity table, point cloud data entity table, typical defects entity table, and BIM model entity table. In addition, different sensors contain work parameters and name attributes, so separate entities are created for the sensors associated with the sensor type name. The logical model of the building comfort and structural safety monitoring spatial database is shown in Figure 2, where "PK" denotes the primary key and "FK" denotes the foreign key.

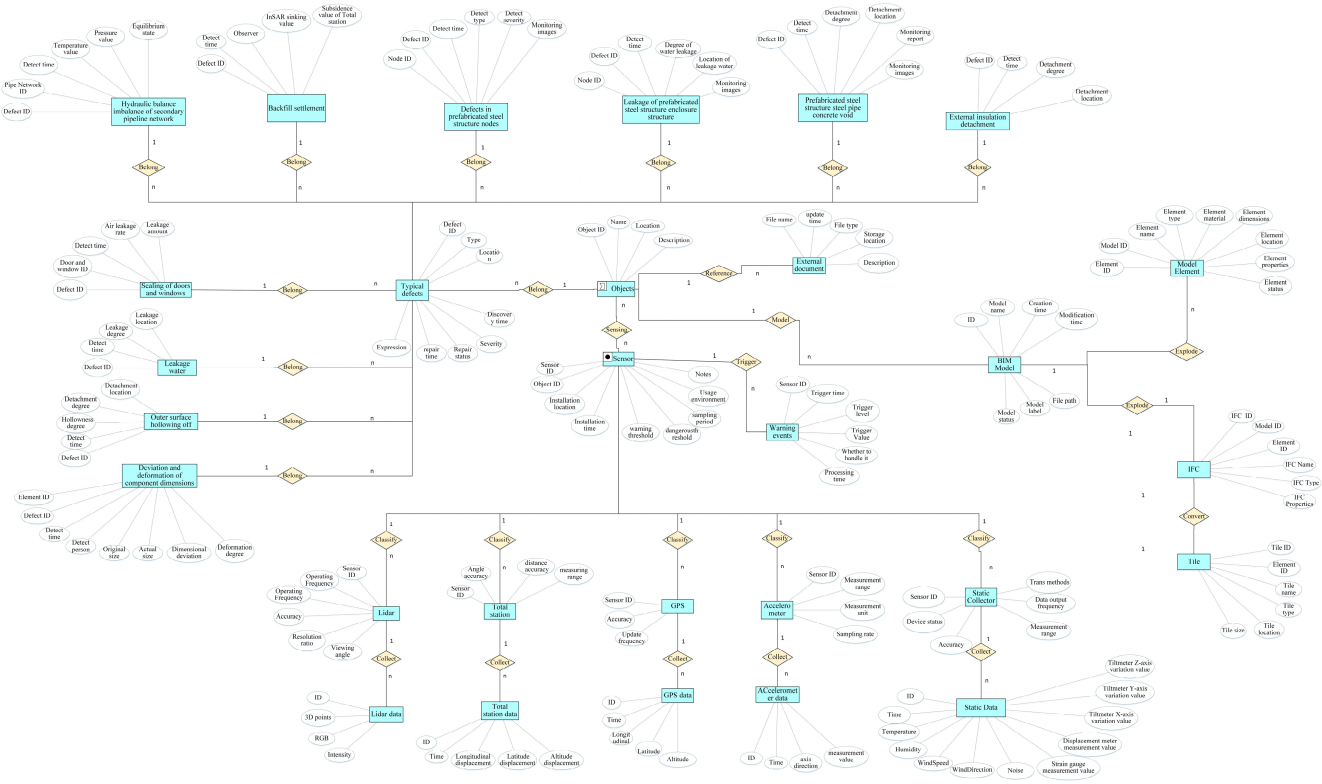


Figure 1. The E-R concept model of building comfort and structural safety monitoring space database.

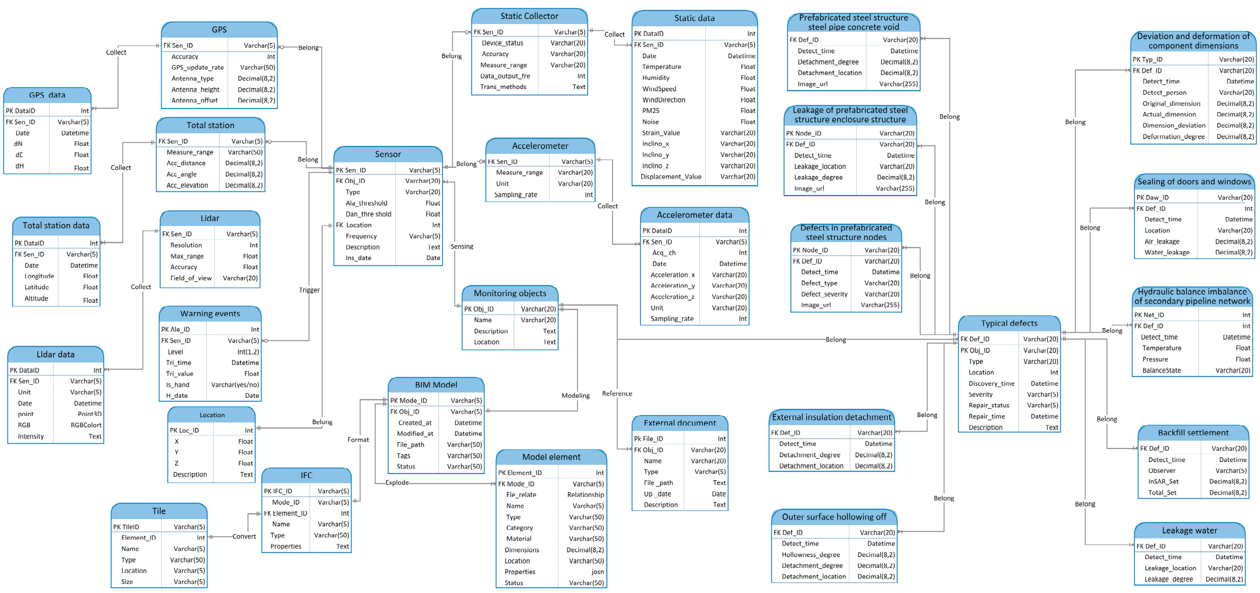


Figure 2. The logical model of building comfort and structural safety monitoring spatial database.

The database developed in this paper is named my_db, and various data tables are created in the database, and spatial index tables are created in it to provide efficient querying and indexing functions for spatial data, to speed up data retrieval, and to improve the performance and efficiency of the database.

2.3.1. Table of Monitoring Data

(1) Table of data on monitored objects

Monitoring of the object data table is used to store building information, and its logical structure is shown in Table 1. The ID is renamed to Obj_ID to distinguish it from the sensor ID.

Table 1. Monitoring object data table.

Field Name	Datatype	Null	Constraint	Description
Obj_ID	Var char (20)	N	PK, Unique	ID of the object
Name	Var char (20)	N		Name of the object
Location	Text	Y		Location of the object being monitored
Description	Text	Y		Any additional notes or remarks pertaining to the object

(2) Table of data on sensor

Sensor-related information is stored in the sensor data table, and this paper only focuses on the independent information of individual sensors without considering the topological network and organization. The logical structure of the sensor data table is shown in Table 2.

Table 2. Sensor data table.

Field Name	Datatype	Null	Constraint	Description
PK Sen_ID	Var char (5)	N	PK, Unique	Sensor ID
FK Obj_ID	Var char (20)	Y	FK	Object ID being monitored
FK Type	Var char (20)	Y		Type of sensor
Location	int	N		Installation location of sensor
Ala_threshold	Float	Y		Warning threshold for alerts
Dan_threshold	Float	Y		Danger threshold for alerts
Frequency	Var char (5)	Y		Sampling period
Description	Text	Y		Description of what is being monitored
Ins_date	Date	Y		Installation date of sensor
Usage_environment	Var char (20)	Y		Environmental conditions in which the sensor is being used

2.3.2. Table of Data on LIDAR Acquisition

The table is used to store the data collected by LIDAR, including 3D point cloud data, color information, reflection intensity, etc. Its logical structure is shown in Table 3.

Table 3. LiDAR acquisition data table data table.

Field Name	Datatype	Null	Constraint	Description
Data_ID	Int	N	PK, Unique	Data ID
Sen_ID	Var char (5)	N	FK	Sensor device number
Unit	Var char (5)	Y		Unit
Date	Date time	Y		Measurement date
point	Point 3D	Y		3D point coordinate
RGB	RGBColort	Y		RGB color
Intensity	Text	Y		Reflection intensity

2.3.3. Table of Data on Dynamic and Static Acquisition

This table is used to store data collected by dynamic and static sensors, including environmental monitoring data (e.g., temperature, humidity, noise level, vibration, etc.), and monitoring data from strain gages, inclinometers, displacements, accelerometers, and other sensors, with a logical structure as shown in Tables 4 and 5.

Table 4. Static acquisition data table.

Field Name	Datatype	Null	Constraint	Description
PK Data_ID	Int	N	PK, Unique	Data Number
FK Sen_ID	Var char (5)	Y	FK	Monitoring Object Number
Date	Date time	Y		Collection Time
Temperature	Float	N		Temperature
Humidity	Float	Y		Humidity
Wind Speed	Float	Y		Wind Speed
Wind Direction	Float	Y		Wind Direction
PM25	Float	Y		Pollutants
Noise	Float	Y		Noise
Strain_Value	Var char (20)	Y		Measured values of strain
Inclino_x	Var char (20)	Y		Change in x-axis of inclinometer
Inclino_y	Var char (20)	Y		Change in y-axis of inclinometer
Inclino_z	Var char (20)	Y		Change in z-axis of inclinometer
Displacement_Value	Var char (20)	Y		Change in displacement measurement

Table 5. Dynamic acquisition data table.

Field Name	Datatype	Null	Constraint	Description
PK Data_ID	Int	N	PK, Unique	Data Number
FK Sen_ID	Var char (5)	Y	FK	Monitoring Object Number
Date	Date time	Y		Collection Time
Temperature	Float	N		Temperature
Humidity	Float	Y		Humidity
Wind Speed	Float	Y		Wind Speed
Wind Direction	Float	Y		Wind Direction
PM25	Float	Y		Pollutants
Noise	Float	Y		Noise
Strain_Value	Var char (20)	Y		Measured values of strain
Inclino_x	Var char (20)	Y		Change in x-axis of inclinometer
Inclino_y	Var char (20)	Y		Change in y-axis of inclinometer
Inclino_z	Var char (20)	Y		Change in z-axis of inclinometer
Displacement_Value	Var char (20)	Y		Change in displacement measurement

2.3.4. Table of Data on BIM Model

The monitoring object is modeled as a BIM (Building Information Modeling) model, which is used to store information about the BIM model. Its logical structure is shown in Table 6. Each model has a unique Model_ID and some associated attributes, such as model name, component name, component contact, creation date, and last update date. Each model has a component data table associated with it, which stores all the component and attribute information of the model, such as the component type, build size, build material, and so on.

2.3.5. Table of Typical Defects

The table is used to record typical defect information, and its logical structure is shown in Table 7. Each defect has a unique Def_ID, and information such as the defect's type, location, discovery date, severity, and repair status is recorded in the table in detail.

Table 6. BIM model table.

Field Name	Datatype	Null	Constraint	Description
Element_ID	Int	N	PK, Unique	Model component number
Mode_ID	Var char (5)	N	FK	Model number
Ele_relate	Relationship	N	FK	Model component relationships (parent component ID, child component ID, relationship type, etc.)
Name	Var char (5)	N		Component name
Type	Var char (50)	N		Component type
Category	Var char (50)	Y		Component category
Material	Var char (50)	Y		Component material
Dimensions	Decimal (8,2)	Y		Component size
Location	Var char (50)	Y		Component location
Properties	josn	Y		Component properties
Status	Var char (50)	Y		Component status

Table 7. Typical defects table.

Field Name	Datatype	Null	Constraint	Description
Element_ID	Int	N	PK, Unique	Model component number
Mode_ID	Var char (5)	N	FK	Model number
Ele_relate	Relationship	N	FK	Model component relationships (parent component ID, child component ID, relationship type, etc.)
Name	Var char (5)	N		Component name
Type	Var char (50)	N		Component type
Category	Var char (50)	Y		Component category
Material	Var char (50)	Y		Component material
Dimensions	Decimal (8,2)	Y		Component size
Location	Var char (50)	Y		Component location
Properties	josn	Y		Component properties
Status	Var char (50)	Y		Component status

3. Analysis of BIM Models Based on Spatial Databases

3.1. BIM Model Format Conversion

Based on the conceptual and logical model of the design, the BIM model is stored in a spatial database for better management and maintenance of building information and provides efficient data storage and retrieval capabilities for the building monitoring system. However, despite BIM models' excellent advantages in data structure and associativity, there are some challenges in the visualization of building monitoring systems. The building monitoring system visualization does not support the regular format of the BIM model and requires format conversion for visualization on the website.

However, BIM models usually have some missing geometric data and attribute information in the data mapping conversion process. In order to realize the non-destructive access of the BIM model into the building monitoring system, this paper proposes a tile organization method based on the BIM model. For the IFC standard model data, based on the hierarchical splitting strategy of component instances of the IFC structural tree, the original IFC files are separated and reconstructed according to the component classification standard of buildings; the reconstructed IFC model files are converted to the glTF format files whose data structure fits the WebGL rendering mechanism, and the dual mapping of geometric space and semantic attributes is accomplished in the process of conversion. It solves the problems of poor model semantic integrity and weak data interoperability in the current integration scheme of IFC standard files and the WebGL framework. At the same time, the converted BIM model, in tile format, is stored in the spatial database, which is convenient for users to call and further analyze in the monitoring system. The BIM model conversion process is shown in Figure 3.

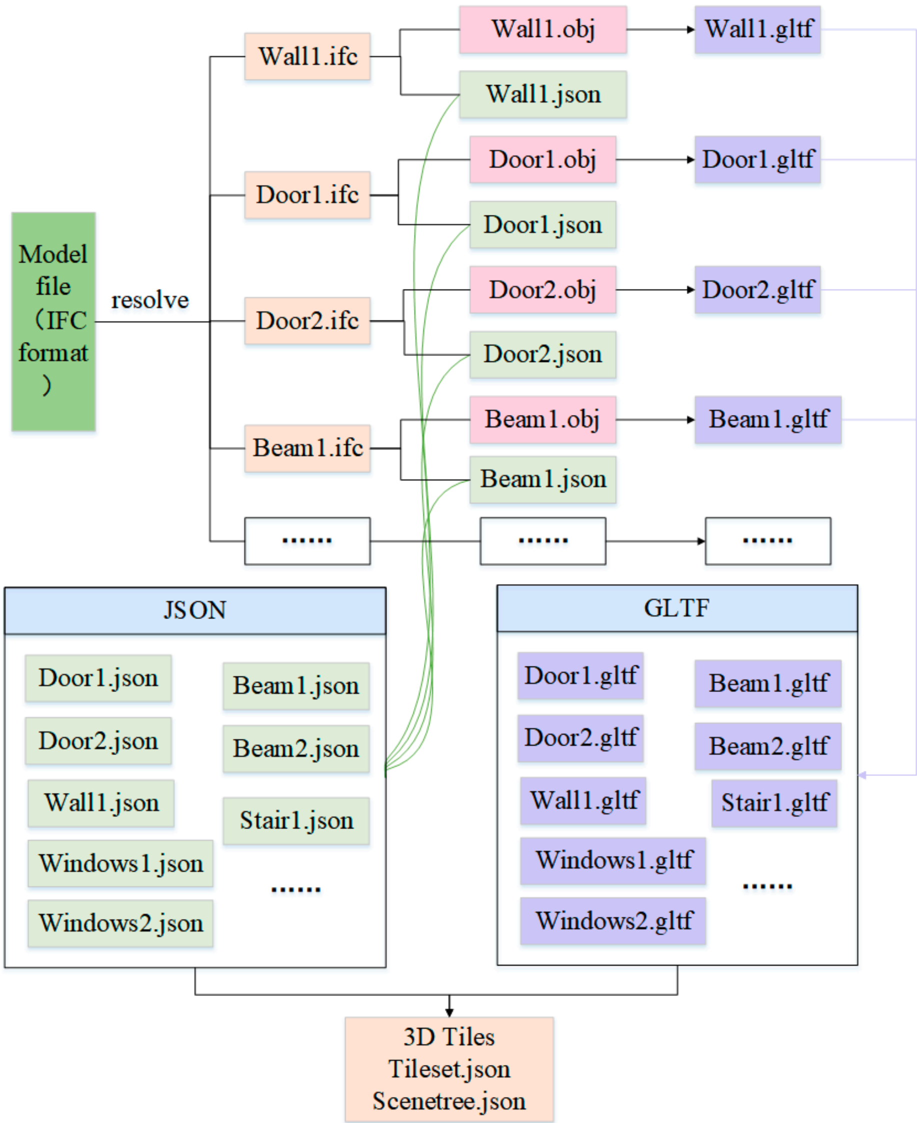


Figure 3. BIM model conversion process.

3.2. BIM Model Interaction

In order to further enhance the experience of using BIM in the building monitoring system, the system provides highly visual and interactive functions of BIM on the website. These features not only enrich the user's knowledge and experience of the building and monitoring data but also help the user to study the thermal environment trends of the building under different climatic conditions and simulate and analyze the impact of different design options on the comfort level.

The spatial database system supports a variety of BIM model operations, such as rotation, scaling, and movement, enabling users to freely view and analyze the BIM model from different angles and scales. The system will provide an interface that allows users to obtain specific element properties by entering query parameters (e.g., element type, name, material type). The user can also select any element and view its attribute information, such as element type, size, and material. The attribute information is stored in the model's metadata, which our system can quickly and accurately acquire and present to the user. Through the presentation of attribute information, users can have a more comprehensive understanding of the composition and characteristics of the building model. In addition, the system also supports the measurement function of the model, which allows users to use the measurement function to obtain information about the dimensions and distances of the components in the building model, which is very important for building design and performance evaluation. Measurements can determine the dimensions of specific areas inside and outside the building or the dimensions of building elements. Measurements can also be used to evaluate the relative positions of different components in a building to analyze the layout and spatial relationships of the components.

The spatial database system also supports the user in performing sectioning operations on the model to study and analyze in depth the shapes, positions, and interrelationships of the components, helping the user to understand the spatial layout and characteristics of the building more comprehensively. The sectioning function allows the user to define one or more sectioning planes through which the model can be sectioned. The planes can be vertical, horizontal, or at any angle. The profiled components are made transparent or hidden, allowing the user to observe the internal structure of the unprofiled components behind the profiled planes, which facilitates the user in identifying potential problems or improvement points. Figure 4 is the BIM attribute query and measurement function, and Figure 5 is the model dissection function.

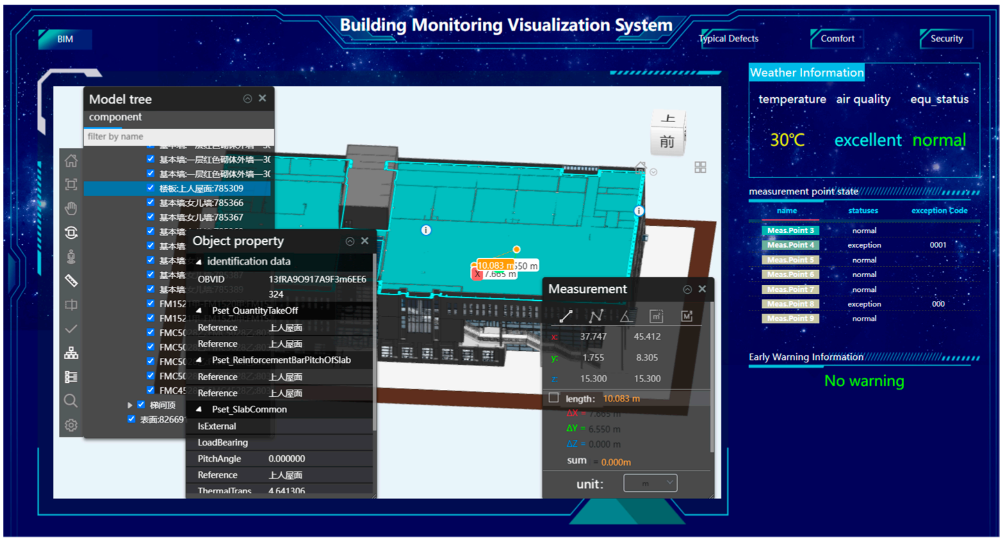


Figure 4. BIM attribute query and measurement function.

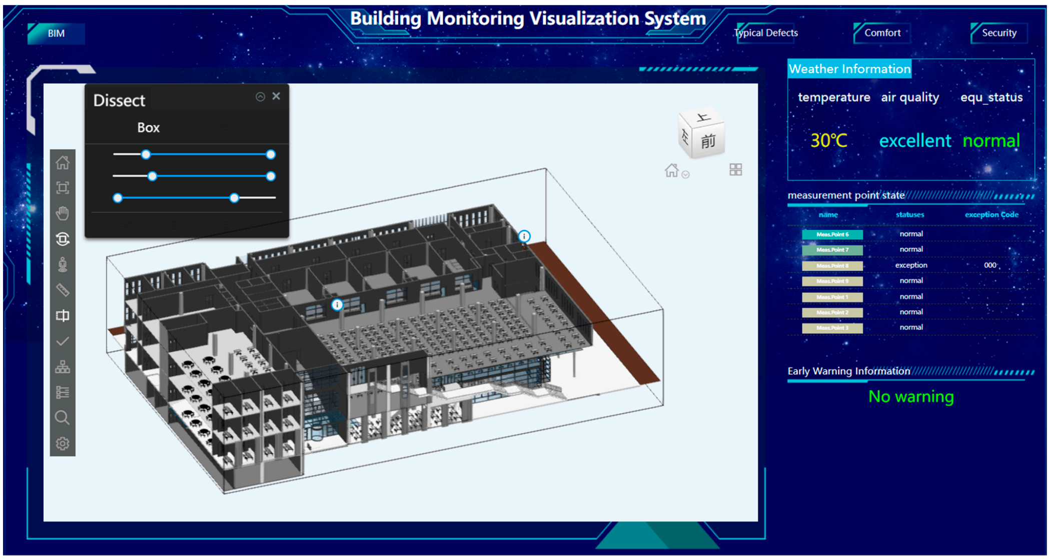


Figure 5. BIM model dissection function.

By realizing the BIM model's high degree of visualization and interaction on the website, the building monitoring system dramatically improves the users' understanding and control of the building environment. The users can study the details and attributes of the building model in greater depth and conduct model analysis and real-time sensor data monitoring, thus promoting the application and development of building monitoring technology.

3.3. BIM Model Analysis

3.3.1. Combination of BIM and Point Cloud Data

3D analysis of the combination of BIM and point cloud data is used to compare the differences between the actual state of the building and the design model. This analysis can reveal changes in building form and help users better understand and manage building projects. The process of 3D analysis with the BIM model and point cloud data is shown in Figure 6.

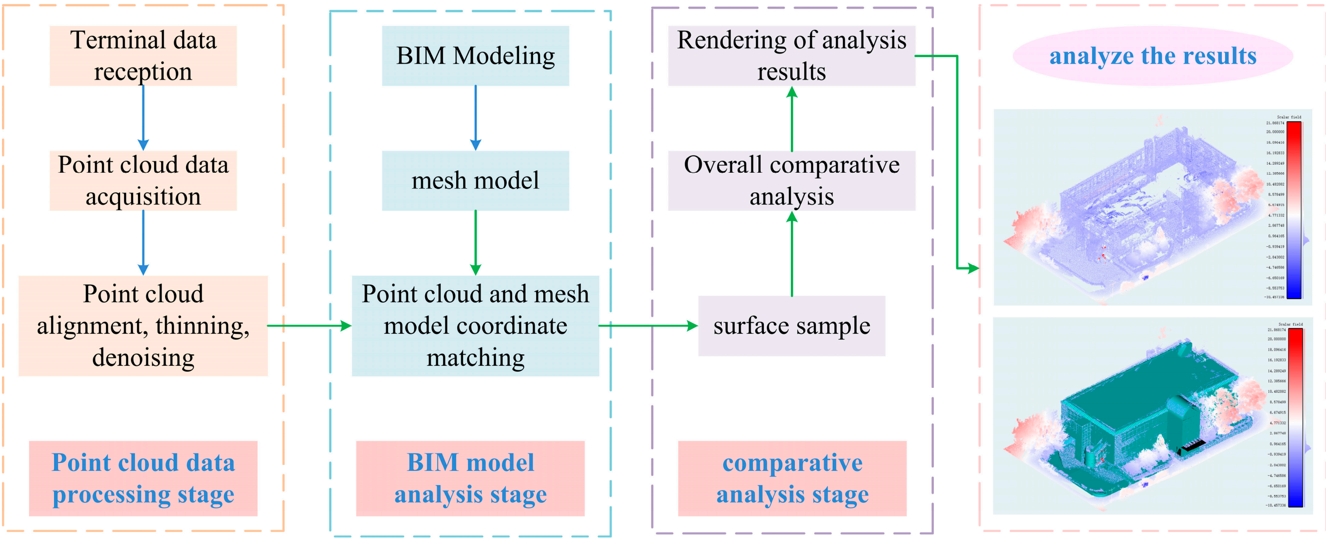


Figure 6. BIM and point cloud analysis process.

First, we process the collected point cloud through alignment, thinning, and denoising while transforming the BIM model into a mesh model. Since BIM models and point cloud data usually use different coordinate systems, we use professional BIM and point cloud processing tools to unify the coordinate system. Then, the point cloud data and mesh model are surface sampled to obtain their surface information. After completing the surface sampling of the data, the distance from each point in the point cloud to the nearest mesh surface is calculated. The point cloud is assigned a color based on the distance deviation so that the user can better understand the difference between the point cloud data and the mesh model. Finally, the 3D analysis results are rendered to the building monitoring visualization system. The results of the 3D analysis are shown in Figure 7.

The combination of BIM models and point cloud data is not only crucial in the design and construction phases that help to better understand the interrelationship between the building and its environment. BIM models allow us to simulate the thermal characteristics of a building under different climatic conditions. Through BIM, we can optimize the design of buildings to improve their energy efficiency and comfort, reduce energy consumption, and thus better cope with the impacts of climate change on buildings. Point cloud data, on the other hand, reflects the impact of extreme weather events on building form and urban infrastructure. Integrating BIM and point cloud data helps mitigate the challenges posed by climate change and supports sustainable development.

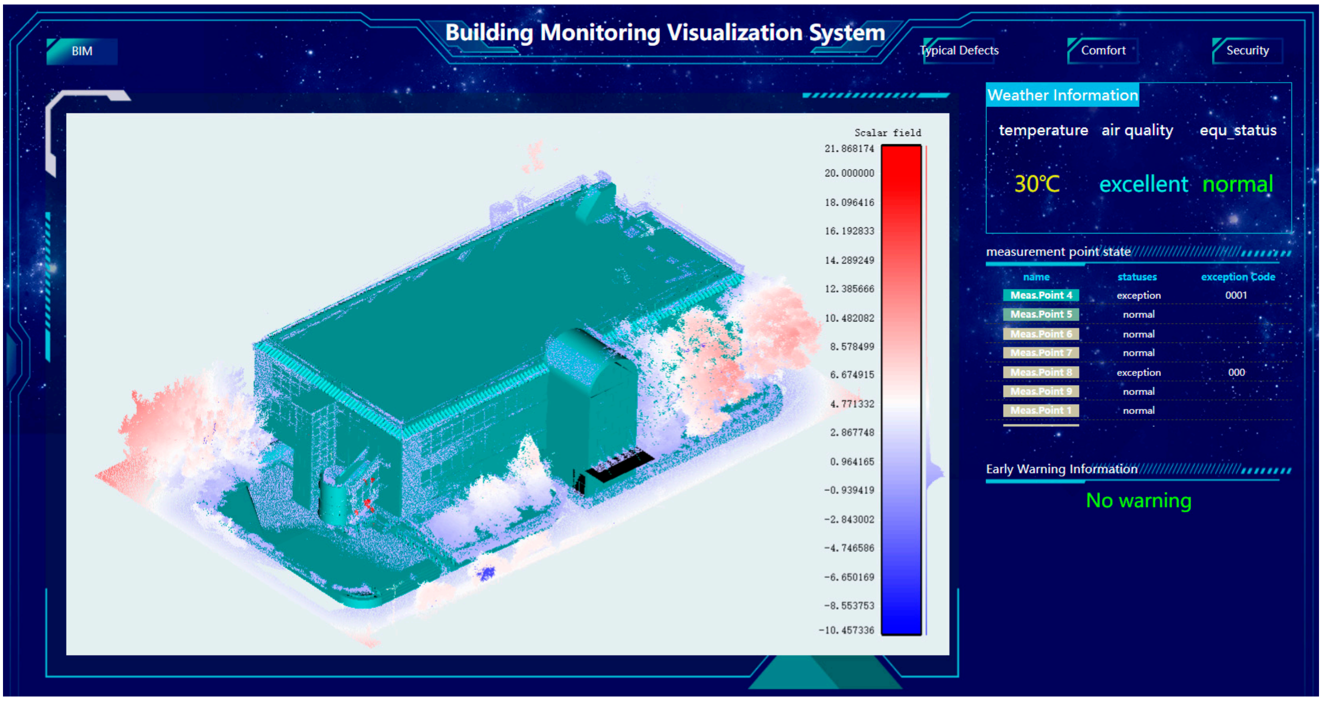


Figure 7. BIM and point cloud analysis visualization.

3.3.2. BIM and Sensor Linkage

Building monitoring systems enable highly interactive and visual monitoring data management by tightly integrating BIM (Building et al.) models and sensor technology. This integration allows users to understand the monitoring systems within a building and access monitoring data in real time. The association of BIM models and sensors extends the BIM model from being a tool for the design and construction phase to the operation and management phases of the building, making the BIM model a "real-time" model. The primary method is to select suitable mounting locations for the sensors based on the monitoring targets and building conditions. At the same time, we put anchor points on the selected sensor mounting locations on the BIM model. These anchor points mark the exact location of the sensors on the model. In this way, we can ensure that the sensors' physical location is the same as the intended location in our BIM model. Then, through the designed data acquisition program, we control the sensors to collect the data and acquire the real-time data from the sensors through the backend technology, which is stored in the database, and, at the same time, sent to the frontend, which, after receiving the data, visualizes the monitoring data in real-time in the form of charts and graphs at the anchor points. That is, through the BIM model's component direct connection function, the component and the sensor position are linked, and the sensor monitoring data are directly associated with the corresponding elements in the model. The monitoring data and the BIM model are fused to become the carrier of the data, realizing the digital twin of the engineering physical world and the virtual world.

Users click on the sensor button in the model, and the corresponding real-time monitoring data chart pops up to visually display the data collected by the sensor. The visual presentation allows users to understand the meaning of the data quickly. The linkage of the BIM with the sensors not only simplifies data management but also provides users of the building monitoring system with a more intuitive and effective way to understand and utilize the monitoring data. This integrated approach is vital in improving data visualization and user experience, contributing to better monitoring and management of building operations and performance. Figure 8 shows the BIM and sensor linkage.

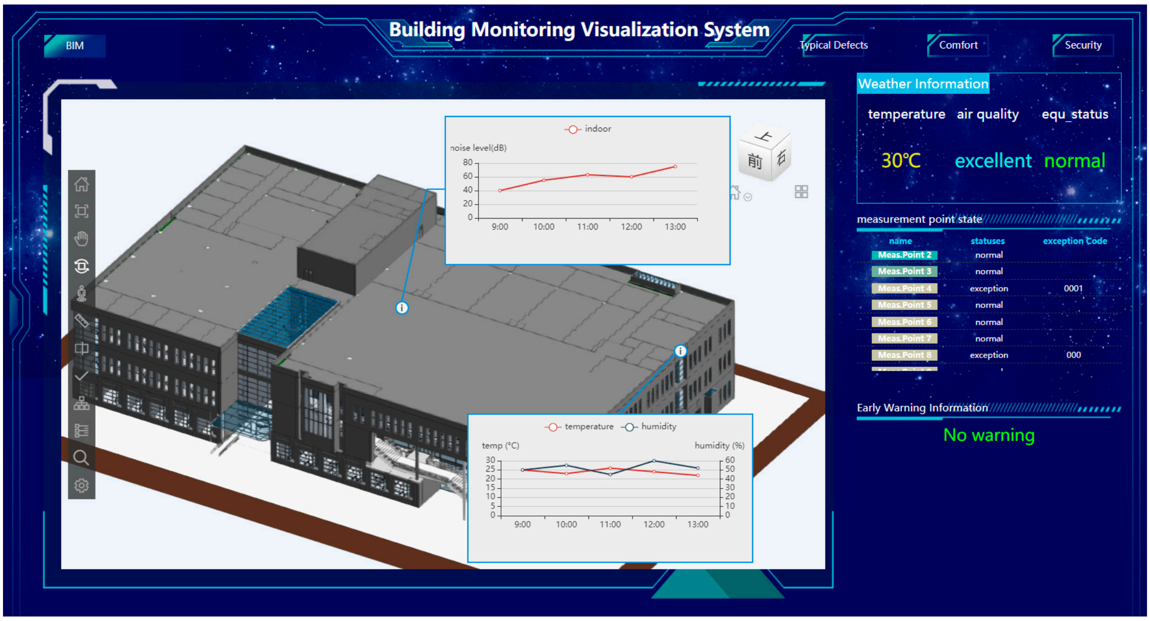


Figure 8. Sensor data display.

4. Spatial Database Management and Visualization

4.1. Spatial Database Management System Platform Architecture

The webpage of the spatial database management system sends requests to the Controller. The Service Layer is used to analyze the coding logic. The Logic Layer transmits a requirement to the Persistence Layer (Mybatis), which interacts with the data tables in the spatial database. Then the results are returned to the Service Layer. Finally, the Service Layer sends the processing logic to the Controller, which the View Layer controls to show the data. Figure 9 shows the structure of the DBMS. Based on the spatial database management system, it is convenient to output data files in formats such as XLS, XLSX, CSV, and HTML, so that the data information can be analyzed and used further [35].

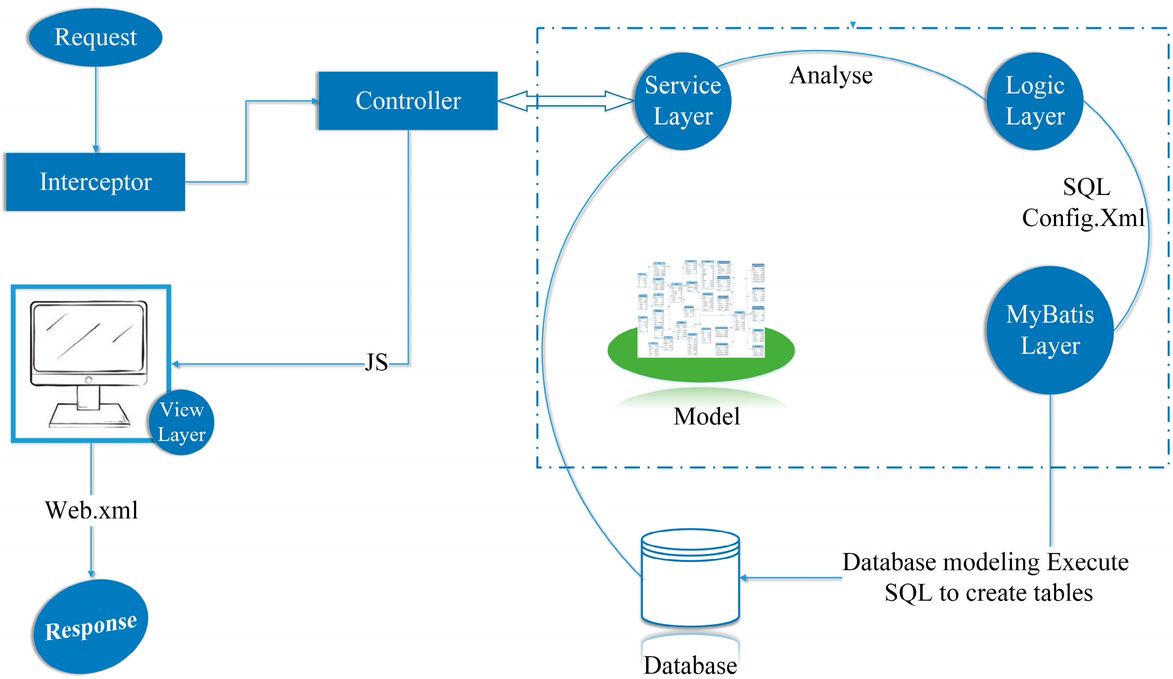


Figure 9. Space database management system platform architecture.

4.2. Overall Process of Building Monitoring

The overall process of building monitoring includes critical steps such as monitoring plan development, sensor installation, data acquisition, data processing, and analysis. First, the monitoring objectives and indicators are determined according to the monitoring needs. The core purpose of this experiment is to monitor the relationship between building comfort and safety and climate change. Building comfort can help analyze the urban heat island effect's formation mechanism and evolution law. The monitoring of structural safety mainly takes into account the influence of the changes in the morphology of the urban building on the flow of the wind field, which leads to changes in the climate. Therefore, the central monitoring indicators include temperature, humidity, noise, air quality, vibration, wind speed and direction, and displacement. For these indicators, temperature and humidity sensors and accelerometers are selected for comfort monitoring; strain gauges, displacement gauges, total stations, GPS, and LiDAR are used for structural safety monitoring. After determining the appropriate type and number of sensors, the layout location of the sensors in the building must also be considered. For example, temperature and humidity sensors should be installed on all floors and in the main rooms of the building, avoiding installation near direct sunlight or air conditioning vents; accelerometers should be installed on the foundation, main support structure, and roof of the building to monitor vibration throughout the building; total stations, GPS and LIDAR, which are used for wide-ranging structural monitoring and topographical measurements, need to be installed on the outside of the building to ensure that there is a clear view; Air quality and noise sensors should be installed in the main living and working areas of the building. The types and number of sensors used for building monitoring are shown in Table 8.

Table 8. Type and number of sensors used for building monitoring.

Sensor	Parameter	Sensor Type	Number
Environmental loads	Temperature, humidity, and PM2.5	Temperature and humidity meter	8
	Wind speed and direction	Propeller anemometer	8
	Noise	Sound Sensors	8
Dynamic response	Vibration	Accelerometer	8
		Dynamic Collector	1
Static response	Strain	Strain meter	4
	Inclination angle	Tilt meter	4
	Displacement	Displacement meter	4
		Static Collector	1
LIDAR	Laser Point Cloud	LIDAR	2
GPS	Longitudinal, Transverse, and Height Displacement	GPS	4
Total Station Instrument	Longitudinal, Transverse, and Height Displacement	Total Station Instrument	4
Total			56

According to the monitoring plan, the sensors are installed at various key locations in the building. The frequency of data collection is set according to the monitoring objectives and the need for data analysis to collect various data from the building's interior and the surrounding environment, such as temperature and humidity, light, noise, and 3D point cloud data. Each sensor is associated with the corresponding location in the BIM model at the time of installation so that the status and data of the sensor can be subsequently displayed in the model. The collected data is transmitted to the server and stored in the object-relational space database via wire networks and wired connections; the collected data are also corrected, converted, and processed to ensure the accuracy of the data. The analyzed data are presented to the user as charts and reports. The overall flow of monitoring is shown in Figure 10.

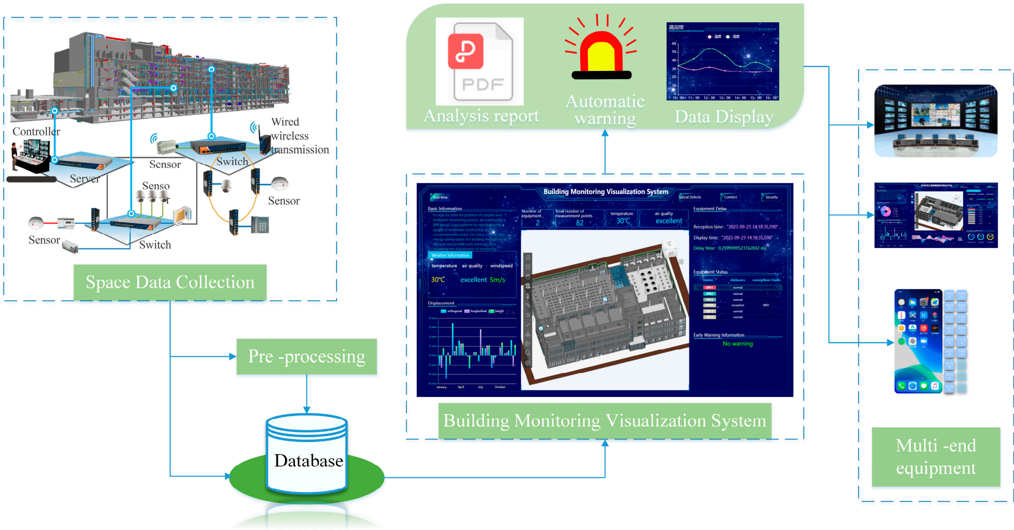


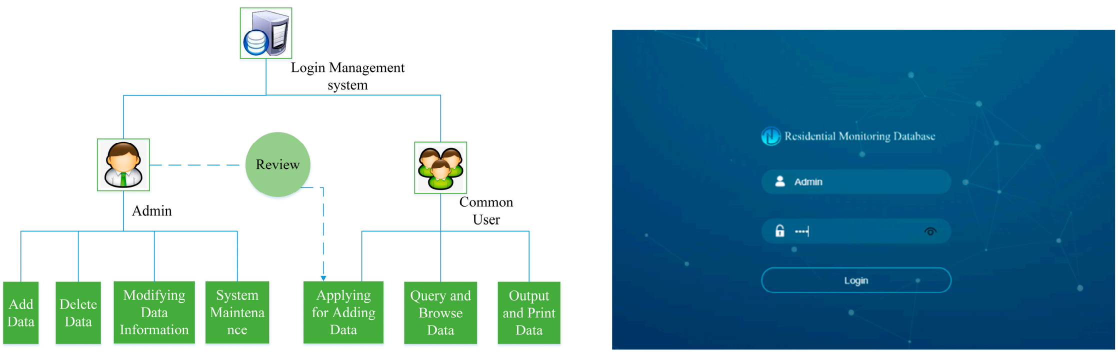
Figure 10. The overall process of building comfort and structural safety monitoring.

By conducting simple monitoring experiments, we obtain the monitoring data of the building and also visualize the data through the monitoring system, which can store and display spatial data such as BIM model data and 3D point cloud data and integrate a variety of sensor data compared to conventional building monitoring databases, which can be used to assess the comfort and structural safety of the building and at the same time provide a data support for further exploration. It also provides data support for further exploring the urban heat island effect and the relationship between building form and climate change.

4.3. Spatial Database System Functional Module

4.3.1. User Management

User management mainly involves user registration, login, permission management, and other links. In the user registration and login session, after receiving the login information, the platform will query the administrator's information table to determine whether the username and corresponding password are correct. If the information is detected correctly, the user can log in to the system and access the privileges assigned by the system administrator; privilege management is one of the core links of user management. The identities of users are divided into administrators and common users. Administrators' rights include adding, deleting, modifying the information of the data, maintaining the system, and reviewing the application items of common users. The rights of common users include browsing, querying, outputting, printing the information of the land data, and applying to the administrator for adding data or files. Figure 11 shows the user management flow chart and login and registration interface.



(a) User management flowchart **(b)** User login registration interface

Figure 11. User management flowchart and user login registration interface.

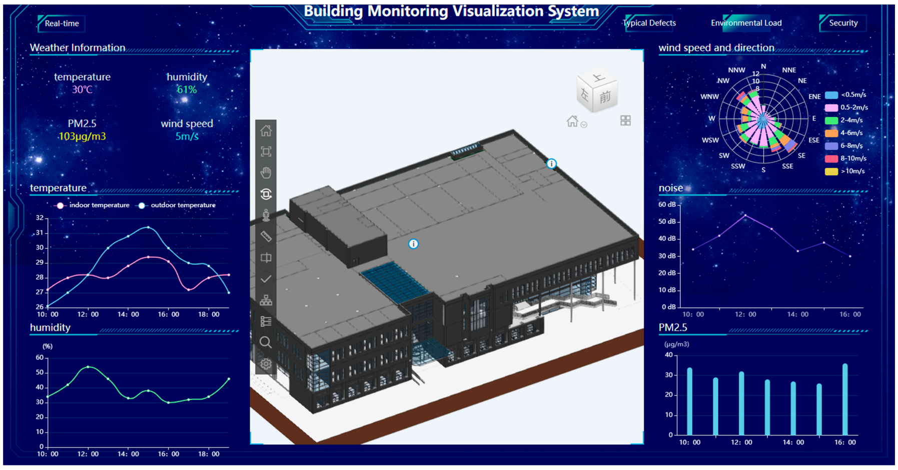
4.3.2. Routine Monitoring Data Management

The data collected from the building monitoring experiments are categorized into five main types according to the application requirements: BIM data, 3D point cloud data, typical defect data, environmental loads, and structural response data.

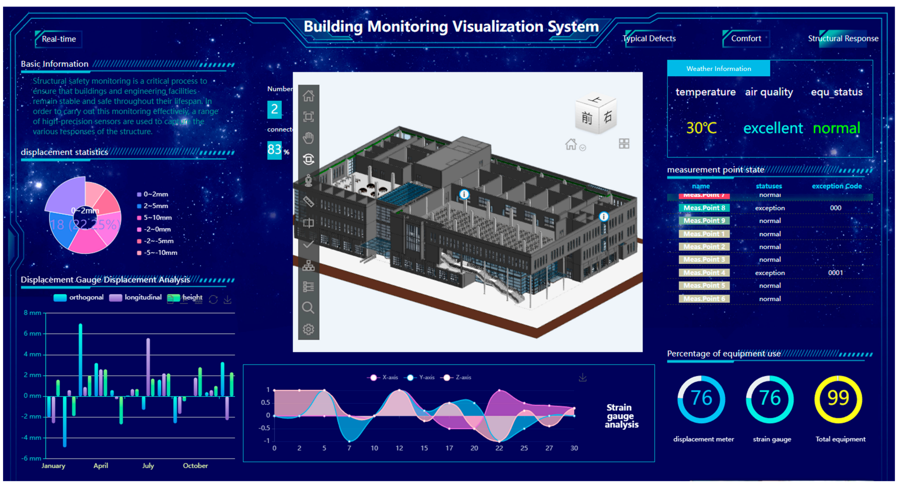
(1) Environmental loads and structural response data

In the field of construction, the data collected using dynamic and static collectors can mainly be categorized into two main types: environmental loads and structural response. Among them, parameters such as indoor temperature, humidity, noise, and PM2.5 reveal the air quality and comfort level of the building, while data such as vibration, displacement, and tilt reflect the structural safety status of the building. At the same time, the analysis of massive environmental parameter data provides a scientific basis for understanding the impact of climate change on the urban thermal environment and managing urban lifelines.

In addition, by visualizing the correlation, distribution, and trend of data from various sensors (e.g., temperature, humidity, light, and noise sensors), the distribution of data can be observed intuitively, and abnormal values that do not conform to the usual pattern can be identified, which is conducive to the detection of malfunction and the early warning and handling of abnormal events of the monitoring system and helps to detect potential problems and take corresponding measures at an early stage. Environmental loads and structural response data management and visualization are shown in Figure 12.



(a) environmental load



(b) structural response

Figure 12. Dynamic and static monitoring data management and visualization.

(2) Typical defects of monitoring data

The Typical Defects Data Management and Visualization feature allows users to manage and analyze typical defect data in a building and provides an intuitive visual display. By categorizing and counting the collected defects data, common types of defects, such as cracks and leaks, and their frequency of occurrence in buildings can be identified. An in-depth analysis of the root causes of defects, the development of appropriate improvement measures and control strategies, and for defects that have occurred, timely measures to repair and rectify the problem are important. Through the analysis of typical defective data of buildings, the quality of buildings can be comprehensively improved, the occurrence of defective problems can be reduced, and the reliability and comfort of buildings can be enhanced.

Combined with the building's BIM model or point cloud data, the typical defects data are displayed in 3D visualization, allowing users to intuitively understand the defects at various locations in the building through the 3D model and further analyze the spatial distribution and correlation of the defects. Meanwhile, interactive analysis and query functions allow users to filter, sort, compare, and analyze the typical defects data according to their needs. Users can query the data according to the defect type, location, severity, and other conditions to obtain specific defect information and statistical results. Typical defects in data management and visualization functions are shown in Figure 13.

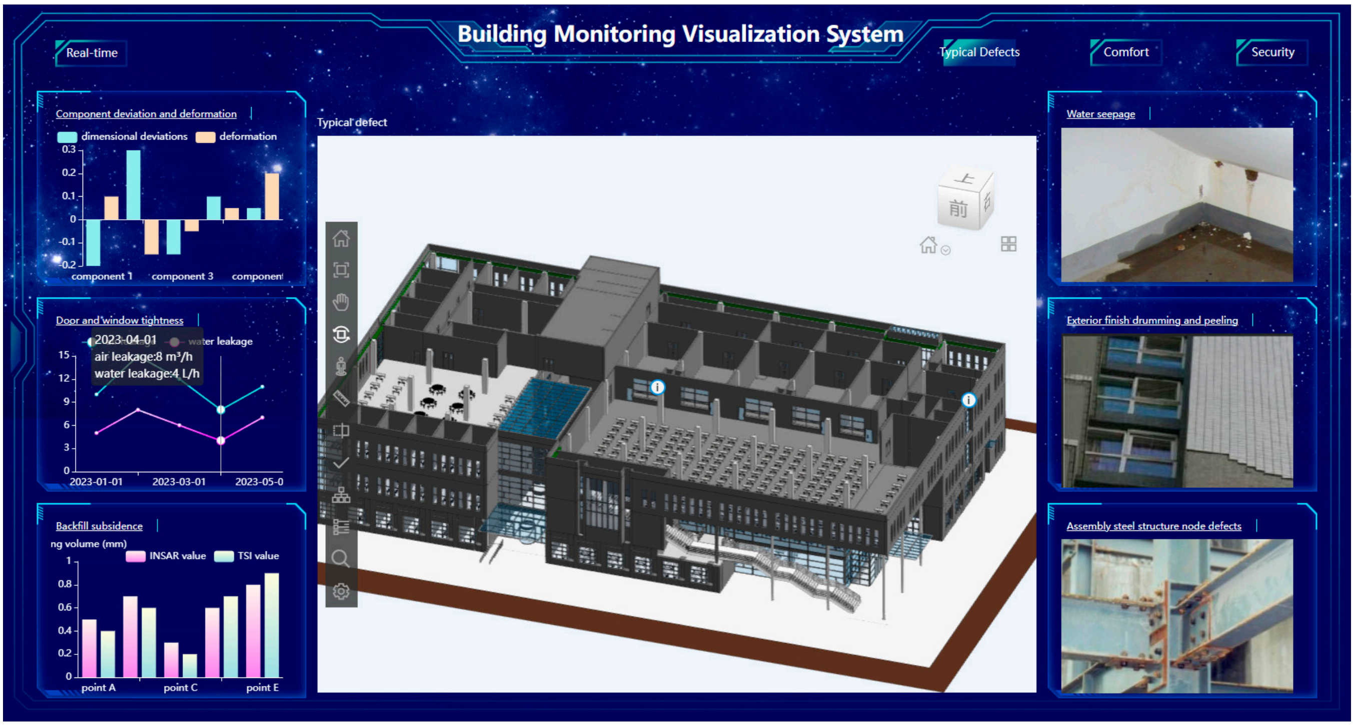


Figure 13. Typical defects in data management and visualization.

4.3.3. Point Cloud Data Management

(1) Point cloud format conversion

In response to realizing the efficient visualization of massive point cloud to point cloud to construct a 3D Tiles tile structure with a multi-detail level, the scene file is segmented into a multi-detail level hash file by an octree segmentation algorithm, the hash file is transformed into point tile data format, and the geospatial location, rotation matrix, geometric error, and other information of the tile data are generated into index files according to the octree spatial data structure. Finally, the 3D Tiles structure is generated. The process of constructing 3D Tiles from point cloud data is shown in Figure 14.

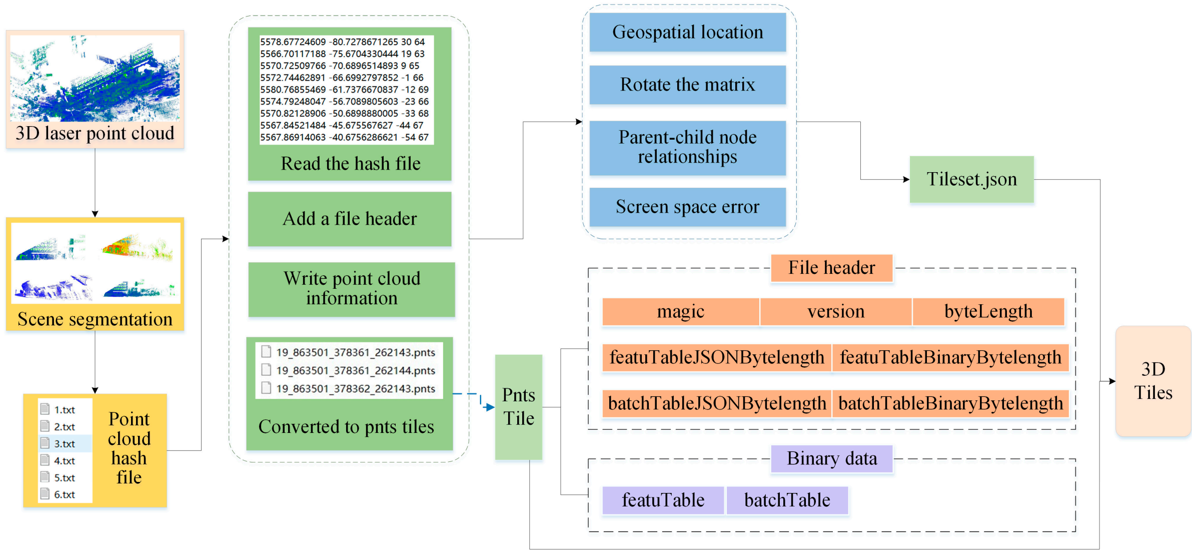


Figure 14. Point cloud data format conversion.

(2) Point cloud data management

The system supports effective management and organization of point cloud data. Through frontend and backend technologies, the stored point cloud data are called from the spatial database and displayed in 3D with the help of efficient visualization; the system supports the color mapping function of the point cloud, which displays the point cloud with different attributes or features in different colors to help users understand the point cloud data more intuitively. Meanwhile, the system provides various operation functions to enable users to flexibly process and analyze the point cloud data, such as rotating, scaling, and moving the point cloud to observe the 3D structure and details of the building. In addition, the system supports measurements and annotations on the laser point cloud. Users can select specific points, lines, or surfaces in the point cloud for measurement to obtain accurate measurement results such as distance, angle, or surface area, which promotes the application and development of the laser point cloud technology in BIM; users can also annotate the point cloud to record important information or problems of the building for subsequent reference and processing. The point cloud data management function is shown in Figure 15.

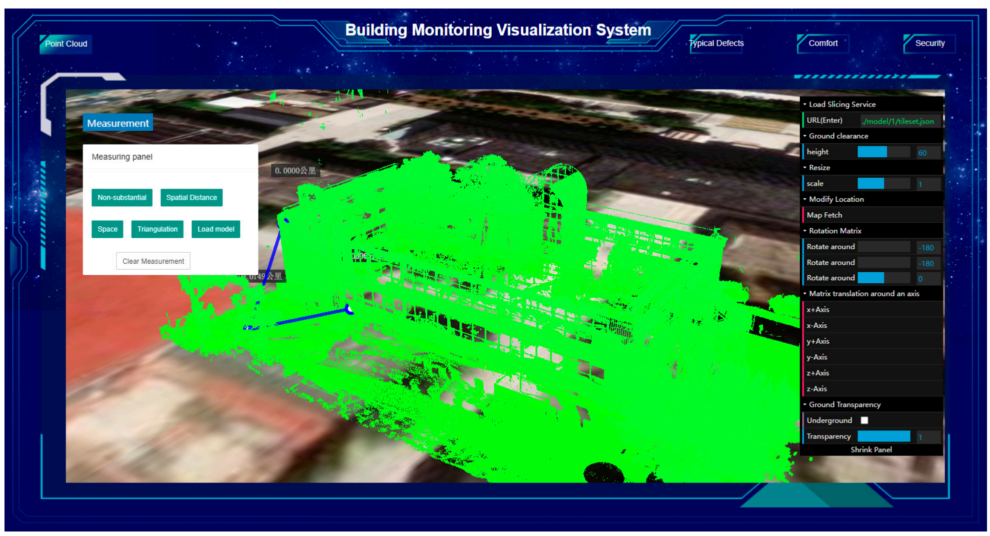


Figure 15. Point cloud management and visualization interface.

4.3.4. GPS Monitoring Module

(1) Data analysis

The GPS monitoring module is mainly designed for deformation monitoring of buildings, utilizing GPS technology's high precision and all-weather measurement characteristics to observe and analyze the horizontal displacement of buildings comprehensively. The GPS receiver acquires satellite signals and records the measurement data. The raw GPS data are analyzed and decoded to obtain information such as satellite position, time stamp, and signal strength and stored in the spatial database. Then the data leveling processing is carried out according to the receiver coordinates, mainly by comparing the measurement data of the reference station and the mobile receiver, calculating the difference between the two, and applying the difference to the measurement data of the mobile receiver. The leveling processing can eliminate the error and noise, and correct the measurement data, to obtain a more accurate positioning result. In addition to the essential positioning and leveling processing, the GPS monitoring module can perform time series and wavelet analyses to remove noise and roughness and retain the actual displacement. The GPS data processing flow is shown in Figure 16.

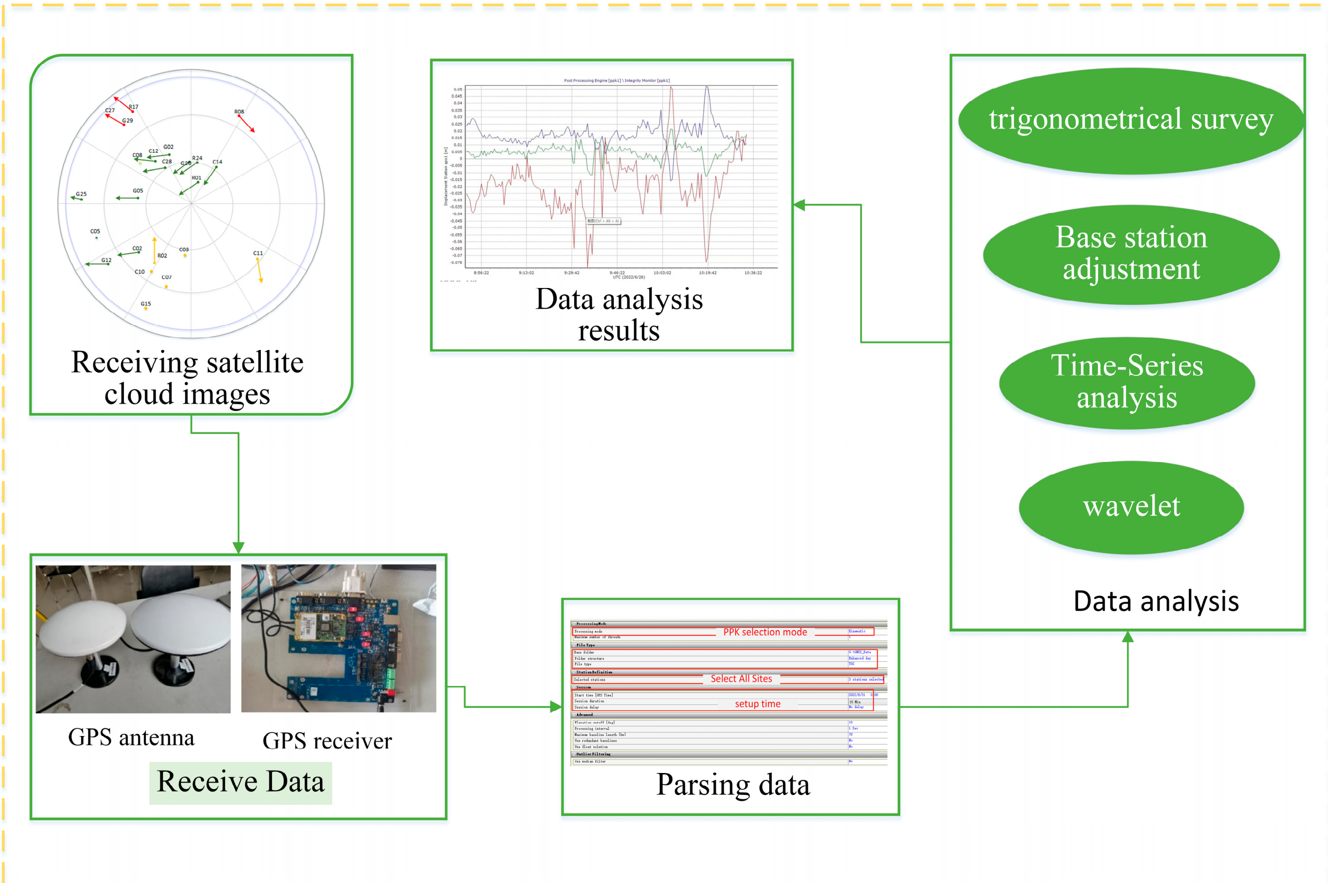


Figure 16. GPS data processing.

(2) Data visualization

Based on the spatial database for building comfort and structural safety monitoring, GPS data are integrated with the BIM model to achieve visualization and analysis of the realized data. Marking GPS data points in the BIM model enables visual observation of the exact location and layout of the building in the real world, and comparing the displacement in the GPS data with the original location in the BIM model enables intuitive observation of the changes in the structure of the building and the displacement, and at the same time provides the GPS data visualization function, which enables the user to better understand

and make use of the GPS data and discover the patterns and trends as well as potential anomalies and abnormal events so that corresponding measures can be taken on time. The GPS data analysis and visualization interface are shown in Figure 17.

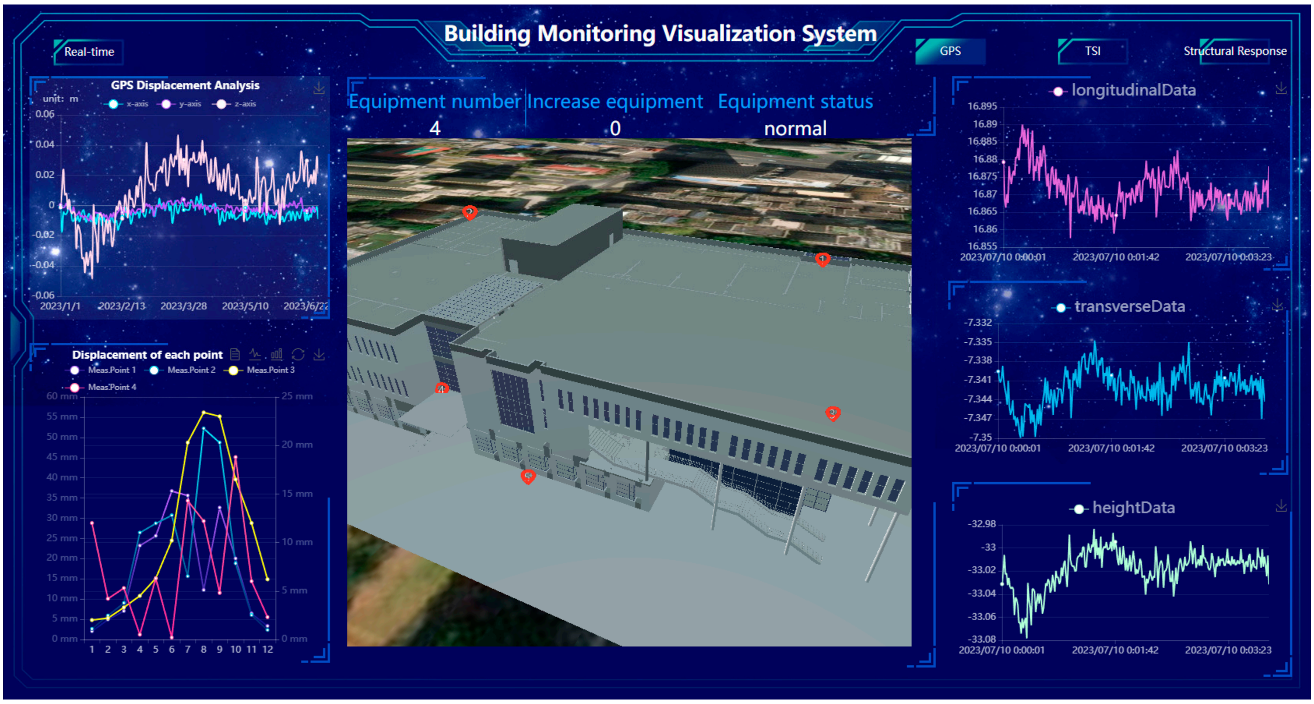


Figure 17. GPS data analysis and visualization.

5. Conclusions

Based on commonly used database tools, this paper proposes and designs the conceptual and logical model of building comfort and structural safety monitoring spatial database according to the demand analysis. Founded on the conceptual and logical structure design, it realizes the object-relational spatial database management system with data storage, management, analysis, and visualization. The system enables the management, analysis, and visualization of building comfort and structural safety monitoring data. It contains many types of data, such as environmental loads, structural response, typical defects, BIM models, and 3D point clouds. BIM technology and 3D point cloud technology are also incorporated into the visualization function to ensure complete building monitoring, enabling any potential problems to be quickly located and identified. The spatial database management system for building comfort and structural safety monitoring developed in this paper solves the problem of storing and managing the massive amount of monitoring data generated in the process of building comfort and structural safety monitoring. It provides data support for building comfort and structural safety assessment. It helps researchers to understand better and respond to the impacts of climate change on building and urban thermal environments, which is of significant academic and practical value for promoting urban management and climate adaptation research.

We have only conducted simple monitoring experiments to verify the usefulness of this spatial database. In future research, further application of the spatial database to building monitoring programs is needed to improve and expand this spatial database management system to adapt to different monitoring needs. At the same time, more data analysis functions and predictive models need to be added and combined with artificial intelligence and machine learning technologies to provide deeper data insights, automated data processing, and anomaly detection to enhance the system's level of intelligence further and to provide a more powerful tool for the management of urban lifelines.

Author Contributions: M.G. supervised the research and revised the manuscript. H.Q. conceived the study, performed the experiments and wrote the paper. Y.Z. (Youshan Zhao). and Y.L. provided monitoring equipment support. J.Z. and Y.Z. (Ying Zhang). participated in data collection. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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