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Building Facility Management System Using Sensors and Digital Technologies

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Globally, 50.44% of buildings are over 30 years old. Old buildings have problems such as obsolete safety monitoring systems and poor management efficiency caused by the use of old equipment. For the better management of buildings and their facilities, we developed an efficient management system based on digitized data from sensors in each device that is connected to the system. The system monitored the operation of each device in real time and sent messages to maintenance personnel in case of any abnormality in each device. This system ensured the normal operation of the building and saved costs and energy via efficient functions. The system was developed and implemented for one year. The operation outcome showed the completeness, relevance, standardization, and visualization of collected data and information. It also enabled the effective scheduling of operation and maintenance by querying the data from each device for intelligent building management.

1. Introduction

Rapid urban development in densely populated areas has led to the construction of high-rise buildings, which have caused various maintenance and management problems that require trustworthy management systems. As buildings require more complex facilities, their maintenance becomes complicated, which is related to safety issues. At present, most research on building management focuses on the maintenance of the hardware equipment of the building so there is a lack of research results on how to manage the data and information from the equipment. For the maintenance of old buildings, people often rely on their blueprints in which the details cannot be read owing to deterioration. In addition, old mechanical and electrical equipment in such buildings is not easy to repair in case of malfunctions due to a lack of equipment manuals or professionals who are well aware of the equipment. This may be related to

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major problems that may cause safety concerns. Old buildings have major issues involving electricity, hydraulics, air conditioning, drainage, and ventilation. Such issues lead to inefficient energy use as well as dubious safety. Older buildings face challenges such as outdated safety monitoring systems and inefficient management because of old equipment. This leads to high costs and energy inefficiency. Such problems can be solved by replacing old equipment with new ones, but for the future management of buildings, it is mandatory to install sensors to monitor the operation status of devices, improve the efficiency of operation and energy use, and save management costs. The operation and management of new buildings require an appropriate building information management system that collects relevant data for effective management. Therefore, we developed a system that employs collected sensor data for managing building facilities.

2. Literature Review

2.1 Building information modeling (BIM)

Many new buildings have adopted IoT technology, whereas some old buildings are equipped with only analog closed-circuit televisions, the functions of which are limited to real-time monitoring. The advancement of computer technology allows for various hardware and software for building management. In smart buildings, building management is automated with integrated systems.(1) Such improvement in management technology leads to the improvement of management quality.(2) BIM was proposed by the National Institute of Biological Sciences (NIBS) to apply information technology to the operation and maintenance of buildings. NIBS stated that the International BIM Standard (NBIMS) is a digital representation of the physical and functional characteristics of a facility as a building life cycle to promote shared information resources. The Association of General Contractors of America (AGC) proposed the development and simulation of BIM for the construction, operation, and management of buildings. BIM requires rich data to provide objective guidance and parameters for the management of buildings and analytics using information of 3D views and data for property managers to improve the decision-making process by grasping digital asset information.

Brinda and Prasanna(3) mentioned that BIM demands accurate information on wall systems, structural systems, air conditioning equipment, ductwork, door and window schedules, and finishes. Detailed manufacturer and supplier information is also necessary to collect information on the sizes, areas, and materials of objects in a building. BIM can reduce costs and time required for construction, improve customer satisfaction, and optimize operation and management by ensuring efficient operation in the entire life cycle of the building. BIM applications in different dimensions include the following.

(1) 4D (3D + time): As an on-site coordination model, 3D models with project schedules are necessary to control on-site facilities and estimate the space required for their installation to reduce the possibility of hazardous incidents and improve the efficiency of construction.
(2) 5D (4D + cost): The BIM 5D model is based on the BIM 4D model to which budgeting is added as the fifth-dimension information.

(3) 6D (5D+File): The 6D model enables facility managers to obtain information on maintenance, inspection, replacement costs, installation and maintenance procedures, and online repair of all equipment or objects in a building.

2.2 Laser scanner

To measure the dimension of spaces in a building, 3D laser (LiDar) scanning technology is used as it overcomes the limitations of traditional measurement methods. The 3D laser scanner is used to obtain measurement data by converting point cloud information into digital data. It enhances the accuracy and efficiency of mapping spaces in a building. The 3D laser scanner performs millions of measurements in a short period and collects information in the form of a virtual point cloud. A point cloud is a set of data points in a 3D coordinate system and is used to describe the internal structure of the space.

3D laser scanners such as LiDar(4) and simultaneous localization and mapping (SLAM)(5) provide high-quality and accurate point cloud data that can be integrated into standard BIM(6) modeling. Figure 1 shows the conversion from point cloud scanning to the BIM model, including actual on-site conditions, laser scanning with color, point cloud data, and a BIM model.

Rocha and Mateus(7) used terrestrial 3D laser scanning and digital photogrammetry to accurately record building structures and simplify on-site work by reducing errors. GeoSlam® has released a 3D laser scanning solution for BIM to capture and convert a space into a digital model for planning, monitoring, or managing the construction. It also allows for sharing of project information between operating units. Chen *et al.*(8) studied BIM combined with artificial intelligence (AI)/IoT/geographical information system (GIS)/big data technology to set up the whole life cycle strategy of construction projects. They simulated projects for architectural planning and design to reduce unnecessary time, costs, and resources and improve construction quality and efficiency.

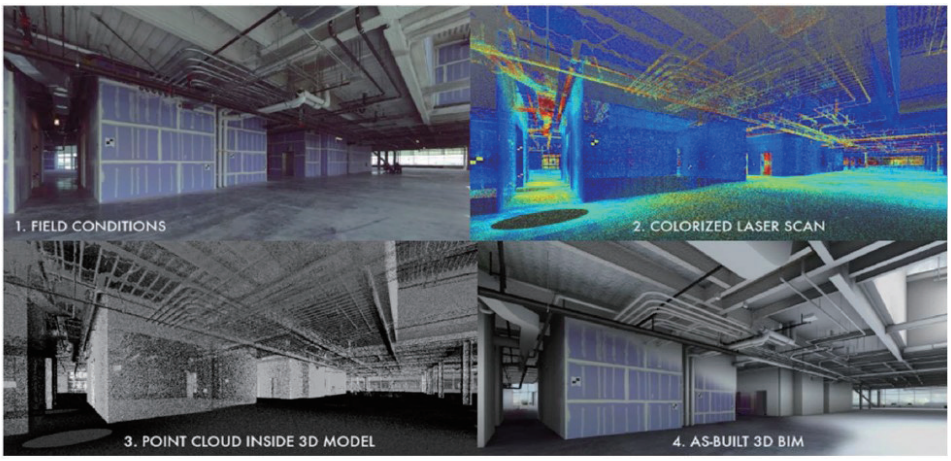


Fig. 1. (Color online) Point cloud data integrated into BIM model.

2.3 Building management system (BMS)

The BMS has been developed with IoT technology in which communication gateways are used with a variety of communication modules for Ethernet, cellular network, Wi-Fi, Bluetooth, ZigBee, and power line communication (PLC). These interact at different interfaces at the same time in the IoT system to transmit and receive data in a network.(9) Operations in the network require cloud computing connected to the Internet infrastructure. This approach is used for BIM with real-time data. The information on the building is obtained and shared using IoT technology and is used for the management of information and resources, structure monitoring, safety assessment, early warning, and controlling functions. Derek(10) studied 60 commercial buildings and found that more than half of the buildings had problems with temperature control, 40% with heating, ventilation, and air conditioning, and about 33% with operated sensors. Such information can be obtained through the integration of BIM and IoT technology. Chen *et al.*(11) pointed out that most energy consumption in commercial buildings was found in lighting (26%), heating (13%), and cooling (14%). To decrease such waste, the IT system developed in this study established a feasible BIM model and provided a shared dynamic infrastructure service.

Smart buildings and houses are the hubs of new digital networks.(12) The 3D BIM is effective in formulating precise improvement projects, making correct energy consumption estimates, and accurately understanding real-time energy consumption.(13) In addition, BIM plays a key role in making the construction supply chain homogeneous and can be used to monitor and reduce CO_2 emissions.(14) The demand for intelligent building management starts with the integration of the centralized real-time monitoring of the equipment and data of the building.(15) The collection of historical statistics and the analysis of construction information, structural information, maintenance information, and maintenance operation data are accomplished using BIM+IoT technology.(11) In the future, artificial IoT (AIoT) will be integrated into smart buildings for building maintenance and operation.(16)

3. Research Methods

3.1 Building for study

In this study, the Taiwan International Trade Building (TWTC) was used (Fig. 2) as a case study. It was constructed in 1988 and has been standing for 34 years. It has a total floor area of 111,821 m^2. Its design was created on hand-drawn blueprints (Fig. 3). The building's facilities require frequent inspections for appropriate operation. In Taipei City, this building is a landmark.

3.2 Investigation and expert interviews

We collected and analyzed information on issues related to the TWTC through investigation, expert interviews, and literature review. The management issues of the building are summarized as follows.

(1) The blueprint was difficult to preserve and read and was worn.

Fig. 2. (Color online) Appearance of the TWTC.

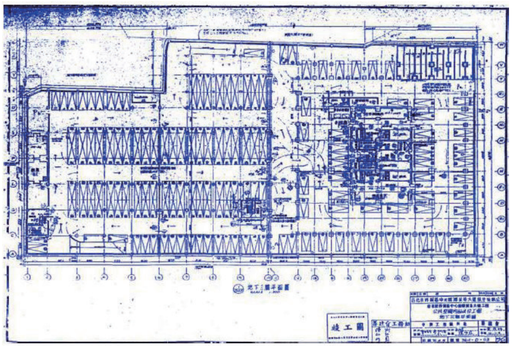


Fig. 3. (Color online) Hand-drawn blueprint of the TWTC.

(2) There was a lack of efficient management, and the maintenance was time-consuming and costly.
(3) Different devices were monitored separately, and it was difficult to integrate information.
(4) Property management companies lack intelligent systems and rely on traditional paper and manual transcription, which resulted in high property management costs.
(5) The equipment was too old for safety monitoring.
(6) Outsourced management companies showed inconsistent performance so it was impossible to establish a sound maintenance system.

For such problems, the required functions of the management system were discussed and defined in interviews with operators and through architecture data analysis. The BIM technology was used to construct a multidimensional digital BIM model as a building facility operation management system.

3.3 Installation of sensors

In the TWTC, mechanical and electrical equipment needed to be replaced. We installed 80 types of IoT sensor connected to the management system (Table 1) to monitor the operation of each device.

3.4 Creation of BIM module

In recent years, BIM has been undergoing digital transformation. BIM is not just a modeling tool but is a core platform for construction project management. AutoCAD has been used as a digital design tool in the construction industry. Since 1990, its 2D digitization method has

Table 1
Sensors connected to management system in the TWTC.

Central monitoring system																
		Digital input (DI)					Digital output (DO)		Communication		System functions					
No.	Device	state	The fault is in abnormal	High-limit surveillance	Low-limit surveillance	Exception alert	Start/stop control	Transferred output	Communication monitoring	Communication control	Alarm monitoring	Timing linkage	Demand control	Dynamic graphics	Data report	Maintenance notice
A	Power systems															
1	Emergency generator	○	○						○		○	○	○	○	○	○
2	Generator tank oil level				○						○			○	○	
3	Generator battery				○						○			○	○	○
4	Residential digital electricity meter										○		○	○	○	○
5	Digital electricity meter in common areas										○	○	○	○	○	○
B	Sanitary water supply and drainage system															
1	Lift water pump	○	○								○			○	○	○
2	Reservoir and tank cover			○	○	○					○			○	○	
3	Roof water tank and tank cover			○	○	○					○			○	○	
C	Fire-resistant switchboard							○	○							
D	Elevator system								○		○	○	○	○	○	○
E	Air conditioning system								○	○	○	○	○	○	○	○
F	Monitoring system															
1	Network dome ceiling camera								○		○			○	○	○
2	Internet gun camera								○		○			○	○	○
3	Fully functional camera								○		○			○	○	○
4	Digital video recorder								○		○			○	○	○

transformed into a 3D BIM design tool. Architects convert architectural elements from 2D- to 3D-based using AutoCAD. The BIM tool has a built-in model library for drawing walls, columns, floors, doors, and window components on the basis of object-based parameters to extract complete 3D height, thickness, and material information model attributes. A BIM model is created by using software such as Autodesk Revit or related 3D modeling software from blueprints. The scanned blueprints are converted into image files and imported by BIM tools for modeling. The BIM tool software imports PDF and image files (Fig. 4) to create a base map and build a 3D BIM model.

Autodesk Recap Pro's built-in measurement tools are used to measure point-to-point distances, areas, and volumes. At the same time, they add markers and measurement points. Figure 5 shows the scenario of the Recap Pro loading point cloud for measurement. These loaded point cloud data are used to extract the parts for conversion and integrate them into BIM software modeling. After the modeling is completed, the Autodesk Recap Pro model saves the result in the point cloud format that can be read by Autodesk Revit.

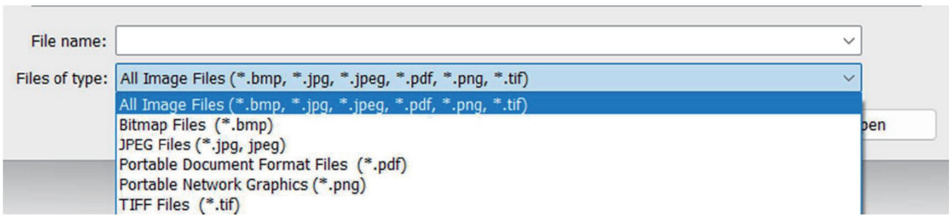


Fig. 4. (Color online) Digital image formats loaded by BIM tool software.

Fig. 5. (Color online) Loaded point cloud measurement data for measure dimensions using Recap Pro loads.

The steps to build a model using point cloud technology include the following.

(1) The BIM software reads the point cloud data and adjusts the coordinate position between the point cloud file and the BIM modeling (Fig. 6).

(2) In the BIM software, floors are switched to accurately calibrate the point cloud, and the point cloud data are rotated by 90° for modeling (Fig. 7).

(3) Modeling is completed, and position correction is conducted (Fig. 8).

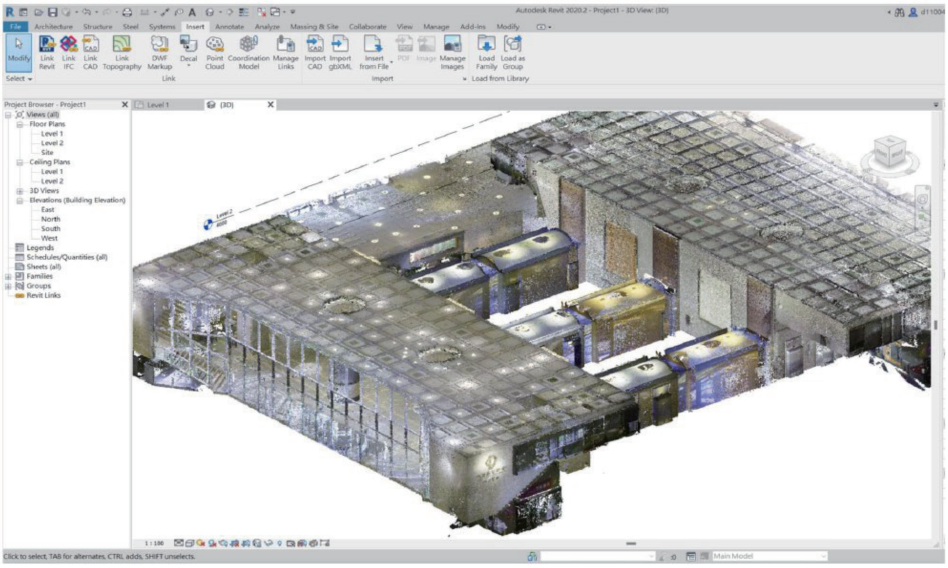


Fig. 6. (Color online) Point cloud data read by BIM software.

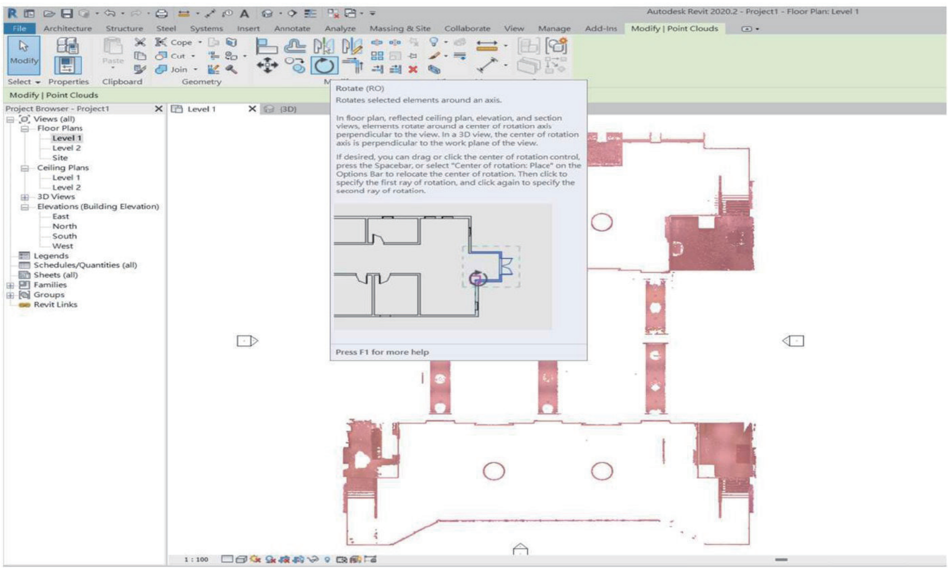


Fig. 7. (Color online) BIM software modeling.

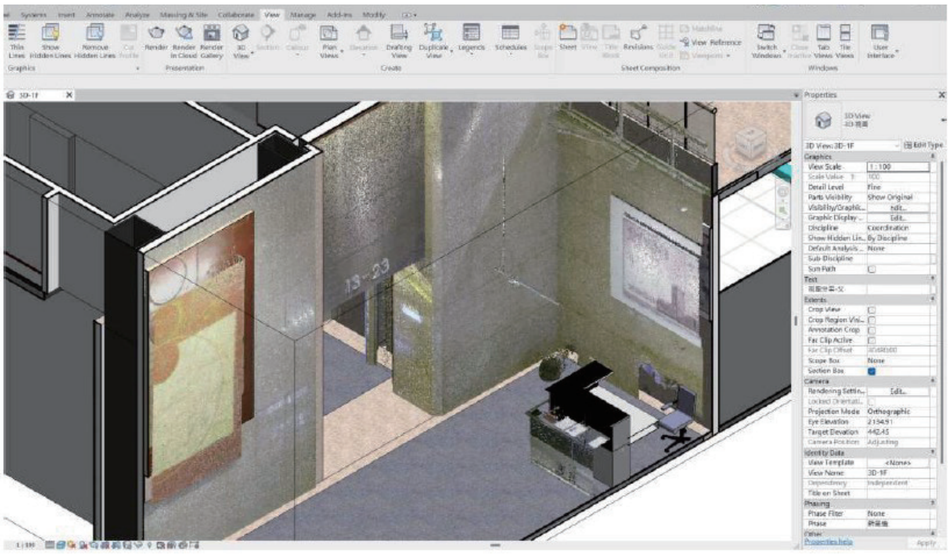


Fig. 8. (Color online) Local position correction.

3.5 Establishing energy baseline using linear regression

An energy baseline, using linear regression, is a statistical analysis method used to study the relationship between energy-related data. In this analysis, the baseline refers to a straight line used to describe the trend or variation of energy data. Through linear regression analysis, one can understand the correlation between energy consumption and other factors, and predict future trends. The main purpose of establishing an energy baseline is to use historical electricity and environmental data, along with current environmental factors, to assist in making predictive electricity use. The method involves obtaining, for examples, statistical data on building energy from a certain period in history, the historical spatial rental rate of buildings, and historical environmental climate temperature and humidity data. These statistical values are then inputted into the linear regression mathematical formula to obtain the energy baseline, which helps in calculating the most likely electricity consumption forecast on the basis of the current rental rate of the building and weather forecast data. In Fig. 9, the blue line is the building's predicted energy baseline.

The mathematical formula for predicting the energy baseline can be applied to the "independent variables" (i.e., environmental factors), including climate temperature and humidity data, and the building's historical electricity consumption (dependent variable). The average monthly electricity consumption for each month of the year is $t_1 \ldots t_{12}$; the average climate temperature for each month of the year is $y_1 \ldots y_{12}$. By using the linear regression mathematical formula [Eq. (1)] to create a predictive model, b_0 and b_1 baselines are obtained.

Fig. 9. (Color online) Building's predicted energy baseline.

$$\min_{b_0,b_1}\left\|\begin{pmatrix}1 & t_1\\ \vdots & \vdots\\ 1 & t_n\end{pmatrix}\begin{pmatrix}b_0\\ b_1\end{pmatrix}-\begin{pmatrix}y_1\\ \vdots\\ y_n\end{pmatrix}\right\|_2 \tag{1}$$

$t_1 \ldots t_{12}$: Historical January–December electricity consumption statistics
$y_1 \ldots y_{12}$: Historical January–December average temperature
b_0: Building energy baseline predicted electricity timeline
b_1: Building energy baseline predicted electricity value

The generated energy baselines, b_0 and b_1, are based on the annual electricity consumption value $\overline{t}$ and the average monthly temperature $\overline{y}$, and the calculation formulas are as follows:

$$b_1 = \frac{\sum_{i=1}^{n}\left(t_i-\overline{t}\right)\left(y_i-\overline{y}\right)}{\sum_{i=1}^{n}\left(t_i-\overline{t}\right)^2}, \tag{2}$$

$$b_0 = \overline{y} - b_1\overline{t} \,. \tag{3}$$

$\overline{t}$: Average annual electricity consumption
$\overline{y}$: Average annual temperature

In this study, we use the Python program to read historical electricity values and climate data, extract climate forecasts from the Central Weather Bureau, and obtain current spatial rental rates to calculate the predicted energy baseline for the accurate prediction of future energy usage.

3.6 System platform

The building facility management system was developed in this study in a browser/server-based architecture with various data and web pages. This system integrated the BIM facility information of the building and combined it with the IoT system. It was developed for environmental monitoring, drainage monitoring, power transformation and distribution, smart lighting, access systems, and fire protection. The system was divided into four subsystems for environmental equipment monitoring, BIM+CPS (Cyber-physical Systems) visualization, operation and maintenance platform, and information data analysis. The system architecture is shown in Fig. 10.

The equipment of the system used two communication protocols, PLC and Modbus, and device monitoring data were sent to the MS-SQL database. In integrating BIM and facility management data (FM), JavaScript Object Notation (JSON) was used to extract, write, and analyze data into the corresponding COBie data table. The system architecture of the software developed in this study is shown in Fig. 11.

For construction–operations building information exchange (COBie) coding, the geometric information of BIM included information on model sizes, assembly shapes, material properties, and material descriptions. Information related to FM was added to the model and the database. The architecture is shown in Fig. 12.

In the BIM model, each building component was assigned an identification number, called an "asset identification". These signs were used for IoT devices to monitor and collect data such as temperature, humidity, and energy consumption. In managing and querying data, dynamic

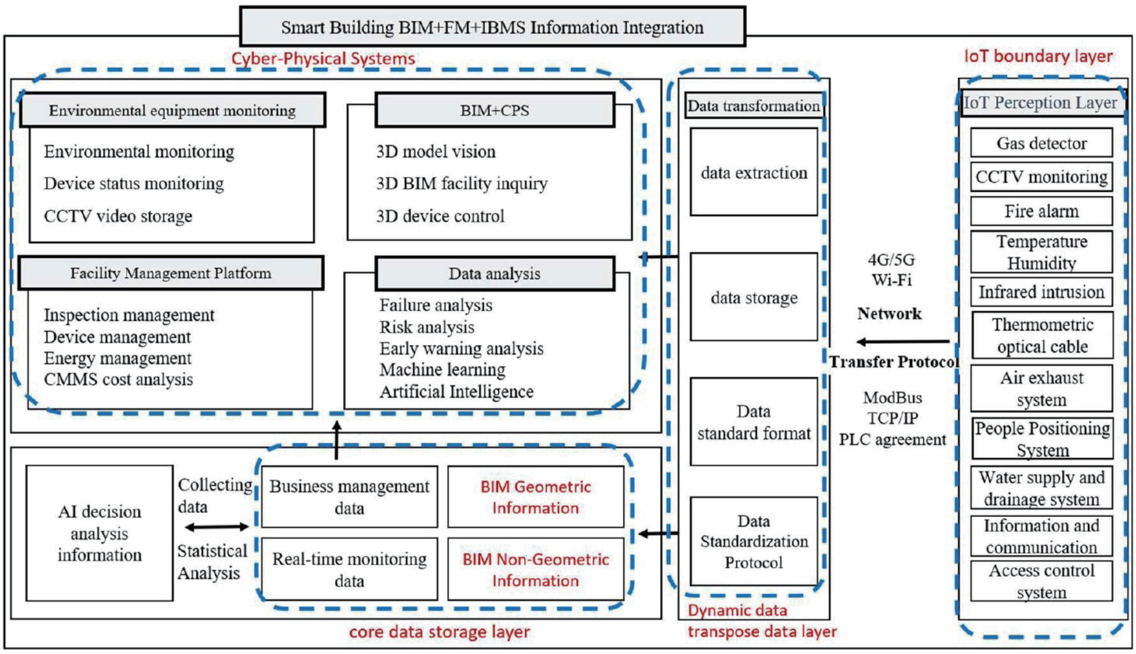


Fig. 10. (Color online) Architecture of developed building facility management system.

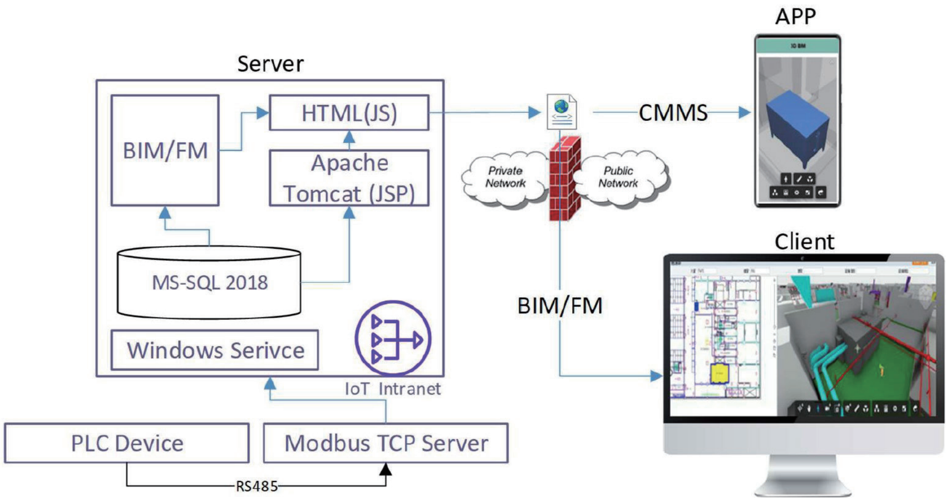


Fig. 11. (Color online) System architecture of BMS and BIM/FM data integration.

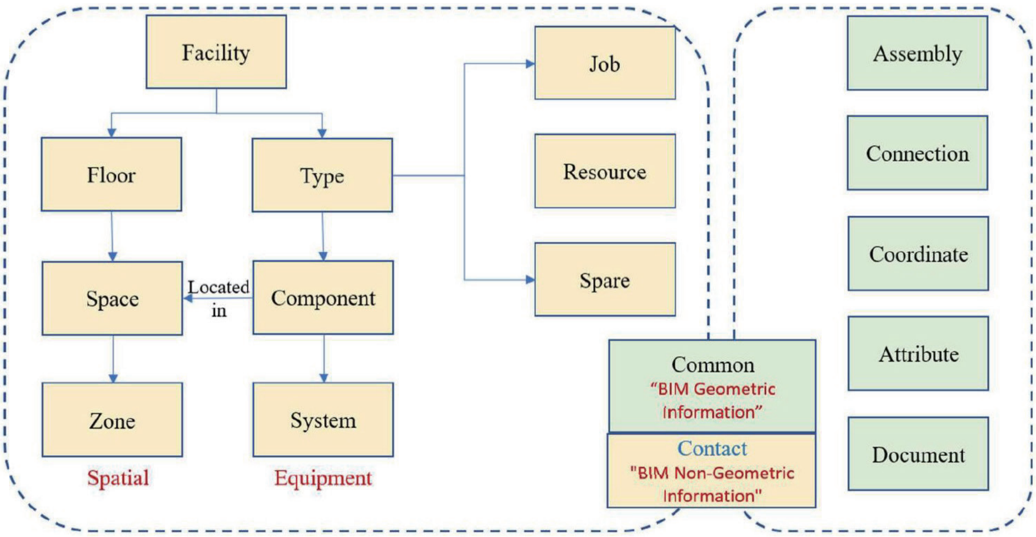


Fig. 12. (Color online) Architecture of COBie coding in BIM.

Modbus needs to be connected synchronously. After the data is transferred and imported into the platform, the Modbus TCP Address field must be synchronized in the corresponding SQL field to correspond to the equipment code (eq_id) of the information table and associated with the BIM model. Correspondence diagram between COBie and IoT data in BIM model is shown in Fig. 13.

(a)

fl_id	rm_id	eq_id	eq_std	category	user1	ip_address	object_id	value_time	status_flages	vaule_max
F02	02-PHONE	02FIEL11	Power System	Electrical	Electrical cabinet	192.168.80.31	3000072	00:02.0	200	110
F02	02-PHONE	PH1CHILLER01	PH1CHILLER01	AHU-1B COIL VALVE	CHW 1 SUPPLY TEMP	192.168.80.31	3000073	00:02.0	100	121
F02	02-PHONE	PH1CHILLER02	PH1CHILLER02	AHU1 SF1 VANE OUTPUT	CHW 2 SUPPLY TEMP	192.168.80.31	3000074	00:04.0	0	121
F02	02-PHONE	OA_DAMPER03	OA_DAMPER03	PH1 SHW 2_ST	OA DAMPER 1 CONTROL	192.168.80.34	3002654	05:02.0	0	100
F02	02-PHONE	RA_DAMPER03	RA_DAMPER03	1F AHU ZN-SP	RA DAMPER 1 CONTROL	192.168.80.34	3002655	05:05.0	0	100
F02	02-PHONE	EA_DAMPER03	EA_DAMPER03	AHU1A_OD1_CTL	EA DAMPER 1 CONTROL	192.168.80.34	3002656	05:07.0	0	100
Field Description										
fl_id	**rm_id**	**eq_id**	**eq_std**	**category**	**user1**	**ip_address**	**object_id**	**value_time**	**status_flages**	**vaule_max**
Floor code	Room code	Equipment number	Equipment standards	Equipment category	Equipment Usage	Device IP	Modbus TCP Adress	Meter reading time		Define the upper limit of meter reading

(b)

Fig. 13. (Color online) Correspondence diagram between COBie and IoT data in BIM model. (a) COBie information and (b) COBie transferred to database.

3.7 IoT communication protocol

Considering the previously used information, the IoT communication protocol was created as shown in Table 2.

4. Results and Discussion

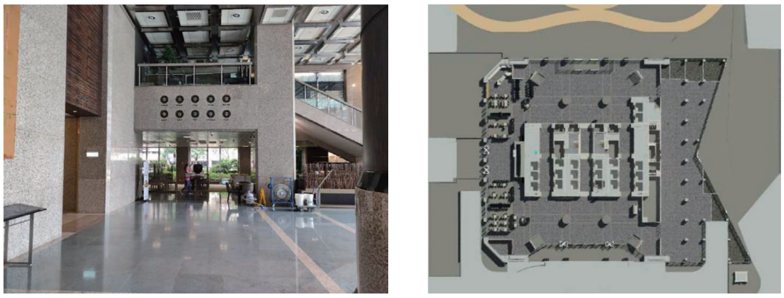
4.1 Results

The existing blueprint data of the TWTC was used to create the BIM model. For the first floor of the building, there was no AutoCAD drawing file. Therefore, 3D laser scanning was used (Fig. 14).

We converted point cloud geometries into architectural elements such as walls, stairs, floors, and windows. At the same time, other attributes and information on materials, dimensions, and functions were added for simulation and analysis (Fig. 15). The same data were used for BIM, FM, and IoT, which led to more efficient and sustainable building management.

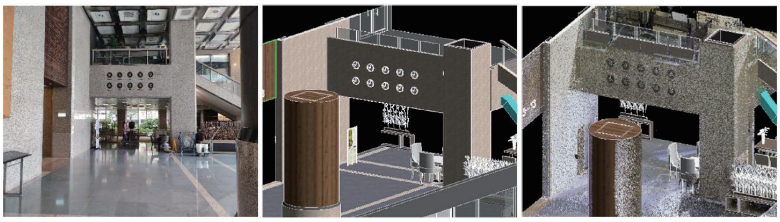
Table 2
IoT communication protocol adopted in the TWTC.

Item	IoT integrates open standards	Application instructions
1	HTML standard	IoT uses HTML format to design graphic control screen programs to meet the needs of open graphics in the application market. In this research project, we used an IoT workstation and a web browser to display the graphic control interface.
2	MODBUS communication protocol for industrial automation systems	In this study, the equipment used MODBUS to integrate PLC into the IoT communication protocol. IoT serves as the "master" of MODBUS and uses MODBUS's RTU, ASCII, or TCP (Ethernet) protocols to integrate the "slave" (SLAVE)PLC.
3	ODBC (Open Database Connectivity, open database interconnection)	This research project corresponds to the stored SQL database and applies the industry standard of database connection (ODBC). IoT provides a read-only ODBC function to read real-time databases.



(a) (b)

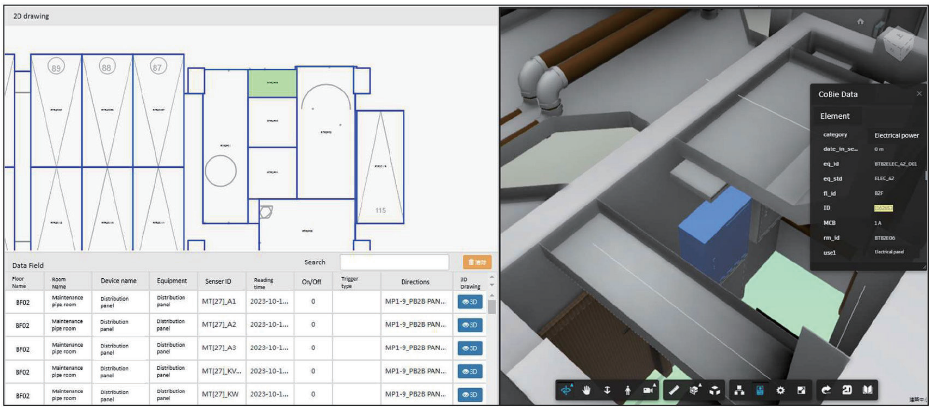
Fig. 14. (Color online) Point cloud data processing. (a) Lobby of the first floor of the TWTC and (b) bird's-eye view of the first floor.



(a) (b) (c)

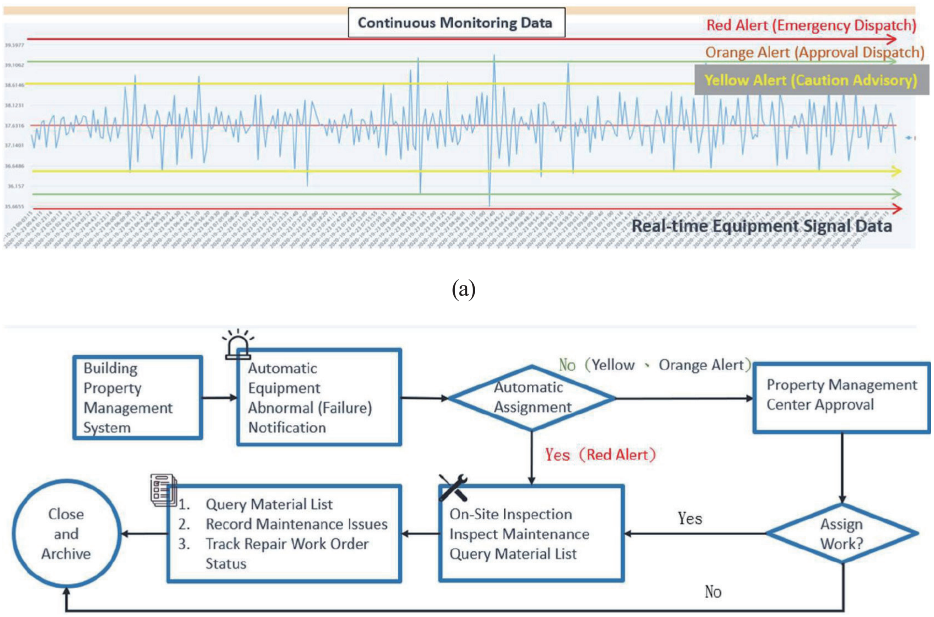
Fig. 15. (Color online) 3D scanning to BIM model results for South Hall on the first floor. (a) 3D laser scan image, (b) on-site photo, and (c) BIM simulation.

In the developed model, equipment failure or shutdown was found in the COBie data link mode of BIM+FM+IoT. It became easier to locate the equipment on the BMS graphic control interface, as shown in Fig. 16. The data link allowed for the visualization of the equipment for efficient and easy inspection and repair. In the developed system, IoT smart monitoring was enabled to predict the wear of devices and establish preventive maintenance plans. Making plans and estimating costs based on the urgency or needs of maintenance became easier with effective process management and reporting. If any abnormality is detected by sensors installed on the devices, the system automatically issues warning information to maintenance personnel to perform some necessary actions to prevent malfunctions or accidents, which improves timely maintenance and reduces time and costs (Fig. 17).



(a) (b)

Fig. 16. (Color online) Web connection screen of BMS+BIM. (a) 2D location of BMS alarm and (b) 3D(BIM) location of BMS alarm.



(a)

(b)

Fig. 17. (Color online) FM+IoT smart dispatch process diagram. (a) Real-time equipment signal data and (b) Equipment maintenance process.

The BIM model was presented in the WebGL format for web browsing and the display of COBie data. For example, Fig. 18 shows the dimensions, height, diameter, and material details of the model.

The BIM model displayed hidden pipelines in the wall, and the relevant information was queried, including pipeline materials, dimensions, installation heights, and system categories (Fig. 19). The system also allowed for measuring dimensions and performing partial 3D cross-section inspection using display functions.

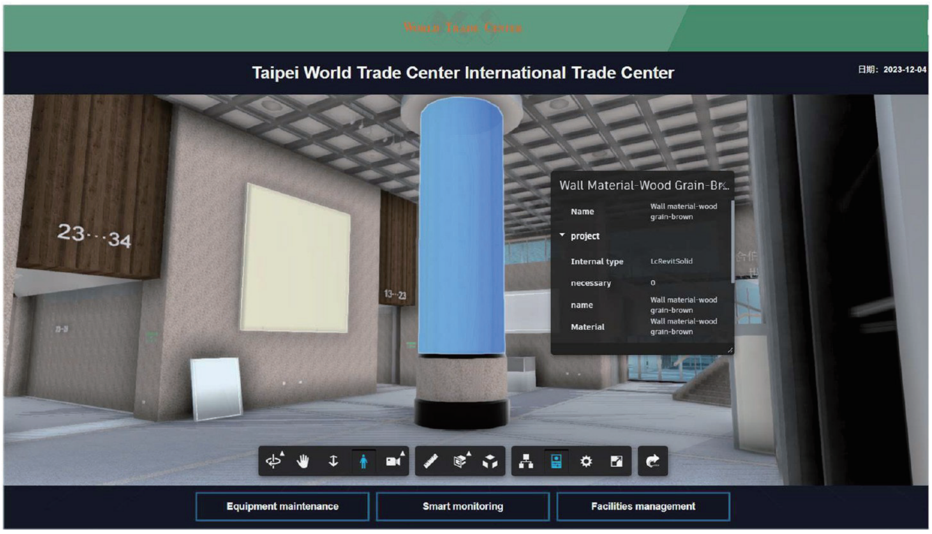


Fig. 18. (Color online) BIM browsing query screen.

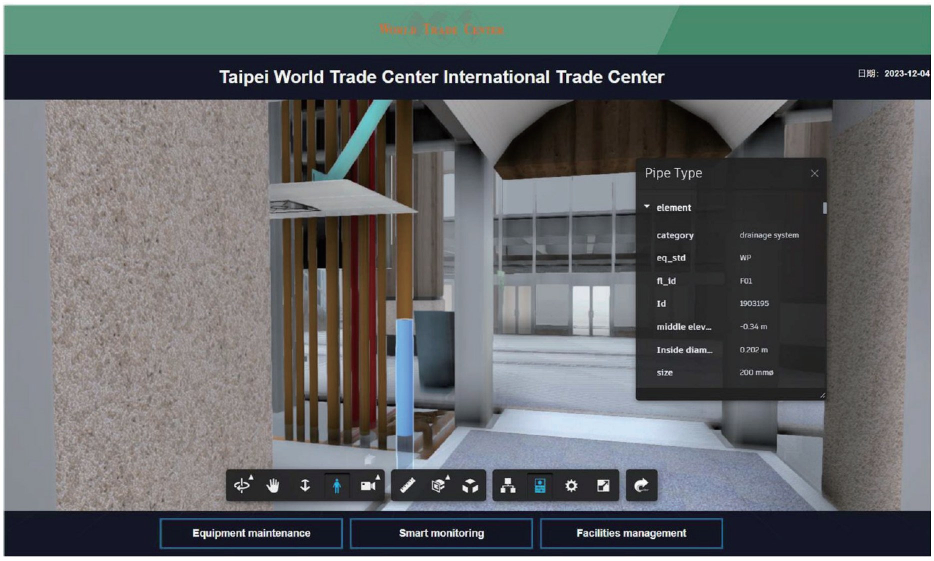


Fig. 19. (Color online) BIM component displayed on browsing screen.

The equipment operation inspection management function of this system can arrange the inspection program form by itself, and can set the inspection cycle according to the inspection content. Inspection cycles include single day, 7-day, 14-day, monthly, quarterly, half-year, and annual. The system can automatically dispatch regular maintenance work orders in accordance with the schedule (Fig. 20). The maintenance record was stored to track the execution and verification of maintenance tasks (Fig. 21).

The developed system continuously and automatically monitored the operating status of the devices. When an abnormality was detected, the system assessed the operating status, reviewed

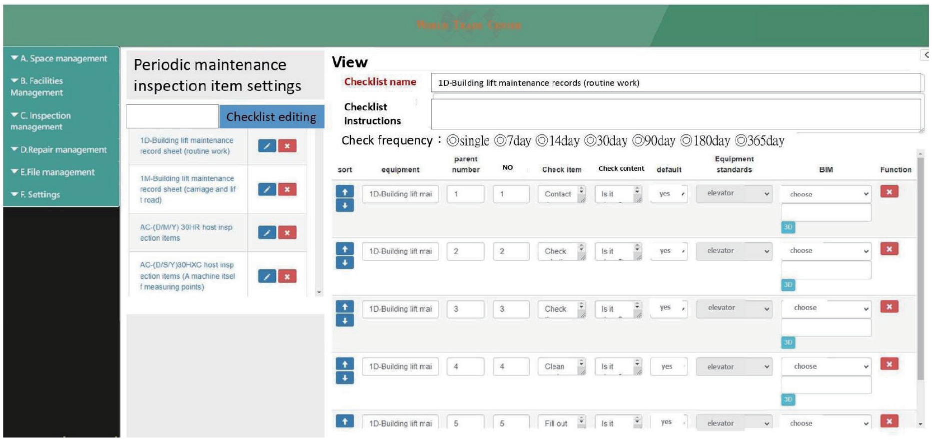


Fig. 20. (Color online) Inspection management functions on screen.

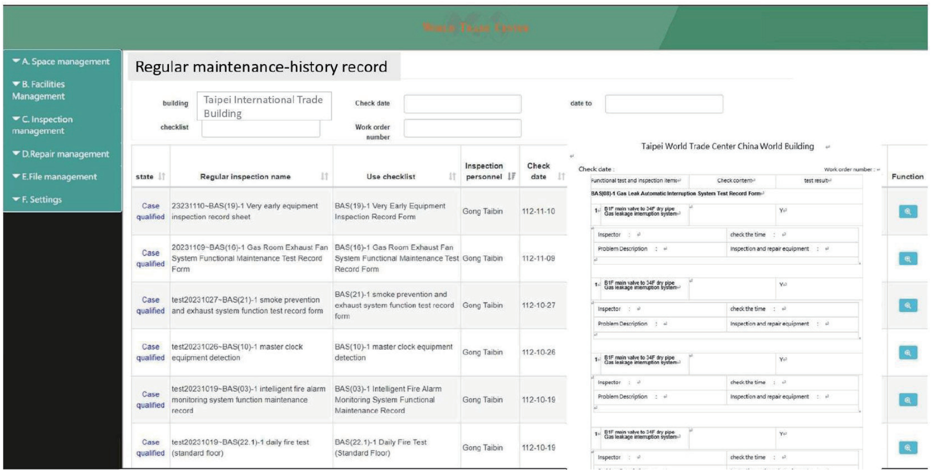
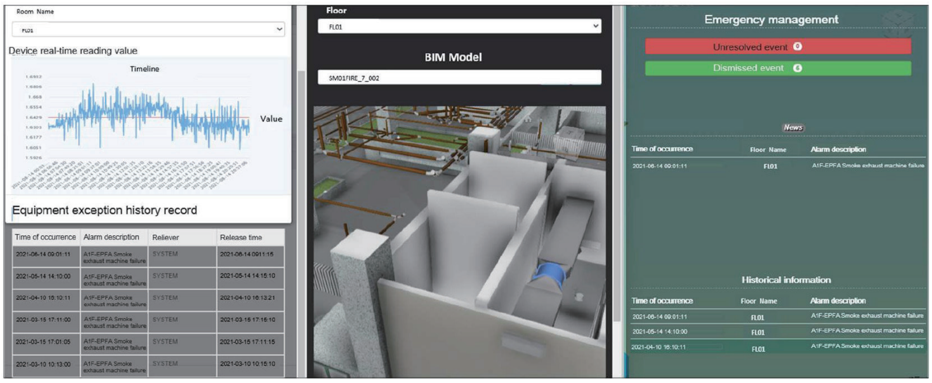


Fig. 21. (Color online) Equipment maintenance record on screen.

monitoring data, and provided a quantitative assessment of problems affecting system operation. If necessary, it sent out a warning notification. The system provided the location and monitoring values of the device. Over the preset threshold, predictive notifications are sent out with accurate locations (Fig. 22). We installed sensors on the devices of the TWTC, and the signals were received by each IP of the device. The real-time data were transmitted to the server computer via Modbus for monitoring (Fig. 23).

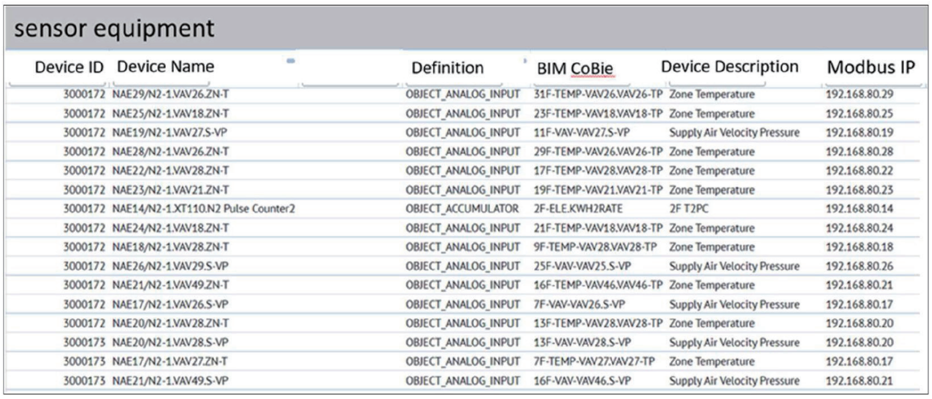
The management function was used by managers to issue maintenance work orders. Maintenance personnel receive notifications, and after completing the repair, a completion report was sent back via the app, Line (Fig. 24).

The management system automatically calculates electricity consumption and creates a table for each device. The proportion of and total electricity consumption in a certain period (set by a user) is displayed. Figure 25 shows that air conditioning accounted for 32.53% of the building's total electricity consumption in September 2023, totaling 461 kW. Figure 26 shows the air conditioning power consumption record from September 2022 to September 2023.



(a) (b) (c)

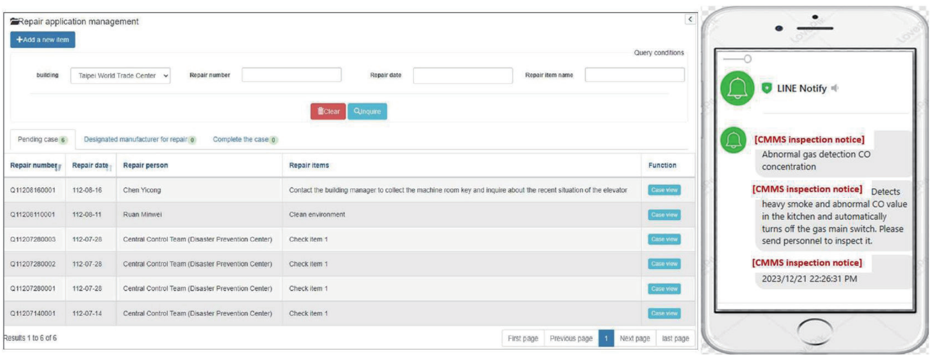
Fig. 22. (Color online) IoT signal detection for locating devices. (a) Real-time device signal data, (b) 3D(BIM) location of BMS alarm, and (c) emergency management display.



sensor equipment

Device ID	Device Name	Definition	BIM CoBie	Device Description	Modbus IP
3000172	NAE29/N2-1.VAV26.ZN-T	OBJECT_ANALOG_INPUT	31F-TEMP-VAV26.VAV26-TP	Zone Temperature	192.168.80.29
3000172	NAE25/N2-1.VAV18.ZN-T	OBJECT_ANALOG_INPUT	23F-TEMP-VAV18.VAV18-TP	Zone Temperature	192.168.80.25
3000172	NAE19/N2-1.VAV27.S-VP	OBJECT_ANALOG_INPUT	11F-VAV-VAV27.S-VP	Supply Air Velocity Pressure	192.168.80.19
3000172	NAE28/N2-1.VAV26.ZN-T	OBJECT_ANALOG_INPUT	29F-TEMP-VAV26.VAV26-TP	Zone Temperature	192.168.80.28
3000172	NAE22/N2-1.VAV28.ZN-T	OBJECT_ANALOG_INPUT	17F-TEMP-VAV28.VAV28-TP	Zone Temperature	192.168.80.22
3000172	NAE23/N2-1.VAV21.ZN-T	OBJECT_ANALOG_INPUT	19F-TEMP-VAV21.VAV21-TP	Zone Temperature	192.168.80.23
3000172	NAE14/N2-1.XT110.N2 Pulse Counter2	OBJECT_ACCUMULATOR	2F-ELE.KWH2RATE	2F T2PC	192.168.80.14
3000172	NAE24/N2-1.VAV18.ZN-T	OBJECT_ANALOG_INPUT	21F-TEMP-VAV18.VAV18-TP	Zone Temperature	192.168.80.24
3000172	NAE18/N2-1.VAV28.ZN-T	OBJECT_ANALOG_INPUT	9F-TEMP-VAV28.VAV28-TP	Zone Temperature	192.168.80.18
3000172	NAE26/N2-1.VAV29.S-VP	OBJECT_ANALOG_INPUT	25F-VAV-VAV25.S-VP	Supply Air Velocity Pressure	192.168.80.26
3000172	NAE21/N2-1.VAV49.ZN-T	OBJECT_ANALOG_INPUT	16F-TEMP-VAV46.VAV46-TP	Zone Temperature	192.168.80.21
3000172	NAE17/N2-1.VAV26.S-VP	OBJECT_ANALOG_INPUT	7F-VAV-VAV26.S-VP	Supply Air Velocity Pressure	192.168.80.17
3000172	NAE20/N2-1.VAV28.ZN-T	OBJECT_ANALOG_INPUT	13F-TEMP-VAV28.VAV28-TP	Zone Temperature	192.168.80.20
3000173	NAE20/N2-1.VAV28.S-VP	OBJECT_ANALOG_INPUT	13F-VAV-VAV28.S-VP	Supply Air Velocity Pressure	192.168.80.20
3000173	NAE17/N2-1.VAV27.ZN-T	OBJECT_ANALOG_INPUT	7F-TEMP-VAV27.VAV27-TP	Zone Temperature	192.168.80.17
3000173	NAE21/N2-1.VAV49.S-VP	OBJECT_ANALOG_INPUT	16F-VAV-VAV46.S-VP	Supply Air Velocity Pressure	192.168.80.21

Fig. 23. (Color online) IoT device signals of the TWTC.



(a) (b)

Fig. 24. (Color online) Repair application management. (a) Maintenance application management display and (b) maintenance notification on Line.

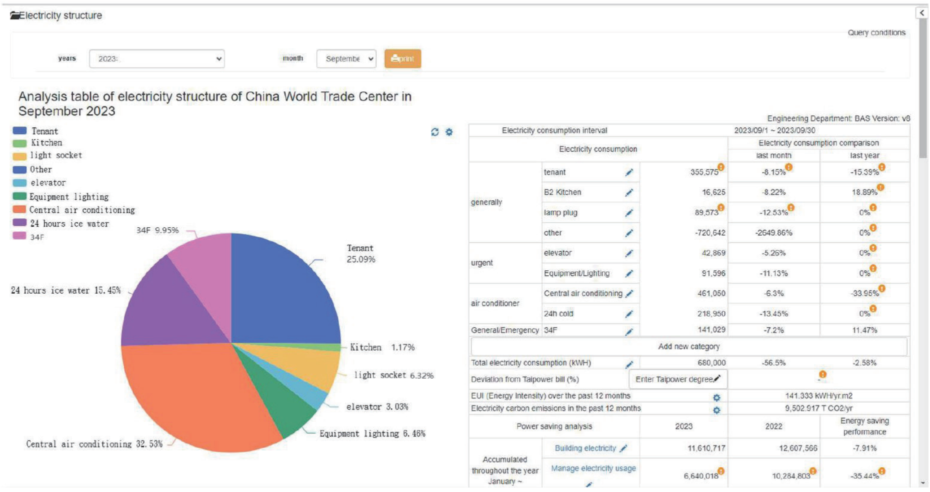


Fig. 25. (Color online) Power consumption analysis for one month.

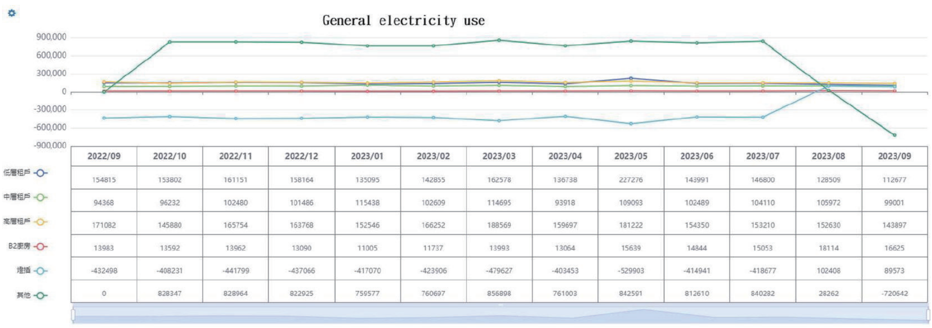


Fig. 26. (Color online) Power consumption analysis for one year.

In this study, we used the building's historical electricity consumption, historical spatial rental rates of buildings, historical environmental climate temperature data, and current spatial rental rates, along with the meteorological bureau's temperature forecast values, inputted into the linear regression mathematical formula to calculate the energy baseline. This will help predict the optimal electricity contract capacity for each half-year period in the future. Figure 27 shows the comparison between the predicted energy baseline and actual electricity consumption from December 2020 to December 2023.

The system also managed digital assets using the asset query function. It displayed 2D/3D images and assets around a device installed. As shown in Fig. 28, by clicking on the Ceiling Monitor Icon, assets were displayed around the installed camera on the ceiling with the location of the camera and assets around it.

The developed system integrated BIM, facility management, and IoT data, allowing for the visualization of equipment, predictive maintenance, and energy consumption monitoring. This improved maintenance efficiency and reduced costs.

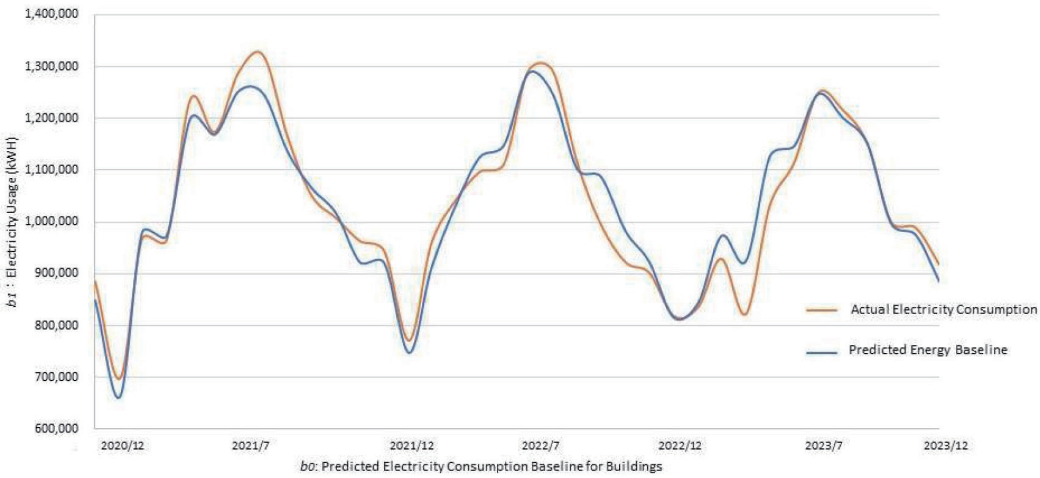
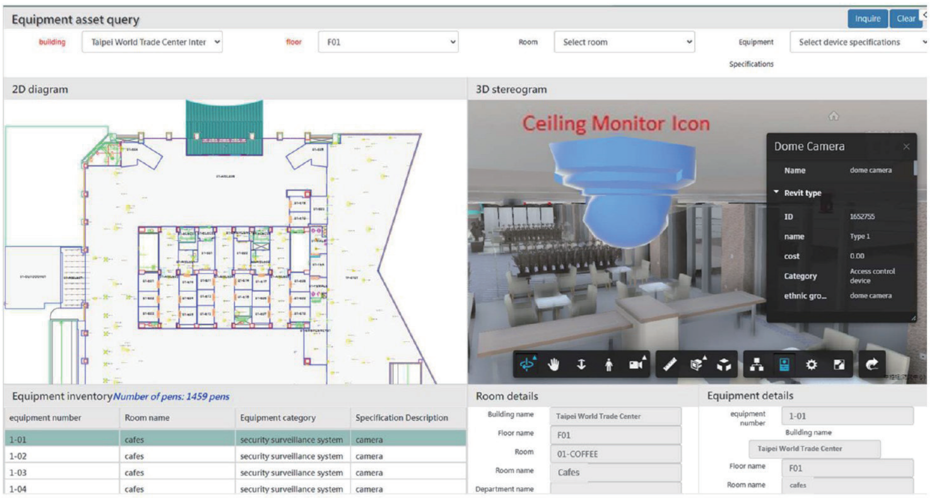
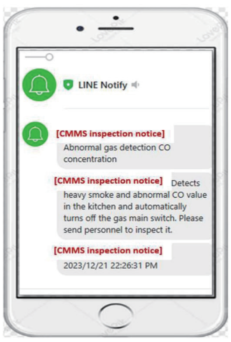


Fig. 27. (Color online) Building energy baseline forecast and actual electricity consumption chart.



(a) (b)



(c)

Fig. 28. (Color online) Asset management in developed system. (a) 2D image of area near device, (b) 3D image of area near device, and (c) Line message to notify maintenance personnel.

4.2 Discussion

We confirmed the locations of the sensors on the devices in the system with the help of Guolin Electrical and Mechanical Company, an electromechanical maintenance device manufacturer. Particularly, in the computer room where frequent inspections are required, sensors are important to monitor signal reception. After installing the sensors, the monitoring results shown in Table 3 were obtained. The results showed that the frequency of inspections was reduced by 50% compared with those of previous manual inspections. This confirmed the effectiveness of the system in reducing inspection frequency and improving maintenance efficiency in the TWTC.

The novelty of this study lies in following key aspects.

A. Integration of BIM and IoT in Building Facility Management

While either BIM or IoT in building management has been explored in other studies, in this study, we uniquely integrated both technologies. This integration allows for a more comprehensive and efficient management system, as it combines the benefits of BIM's detailed modeling with IoT's real-time monitoring capabilities.

Table 3
Installation of IoT monitoring combined with CMMS dispatch to reduce manpower.

Set up IoT monitoring and meter reading devices in the computer room	Perform traditional electromechanical patrol inspection (1 time/month)	Perform manual meter reading and inspection	Use IoT+CMMS detection meter reading to reduce the frequency of patrol inspections (1 time/2 months)	Reduce inspection manpower burden
Fire pump	V	Loss of water pressure Loss of voltage Run overtime	V	50%
Water pump	V	Loss of water pressure Loss of voltage Run overtime	V	50%
Foam pump	V	Loss of water pressure Loss of voltage Run overtime	V	50%
Raised water pump	V	Run overtime	V	50%
Sewage pump	V	Run overtime	V	50%
Waste water pump	V	Run overtime	V	50%
Upper reservoir detection	V	High water level Low water level	V	50%
Lower reservoir detection	V	High water level Low water level	V	50%
Fire pool detection	V	High water level	V	50%
Sewage pond detection	V	High water level	V	>50%
Relay fire pool detection	V	High water level	V	50%
Water level detection in mechanical parking spaces and elevator pits	V	Water level detection	V	50%

B. Focus on Old Buildings
In this study, we specifically targeted old buildings, which often face unique challenges in maintenance and management because of outdated equipment and limited documentation. By developing a management system tailored to these buildings, we have addressed a gap in existing research that tends to focus more on new constructions.

C. Detailed Implementation and Results
In this study, we provided a detailed account of the implementation of the management system in the TWTC, including the installation of sensors, creation of BIM modules, and development of the system platform. Furthermore, we presented concrete results and outcomes of the system's operation, demonstrating its effectiveness in improving maintenance efficiency and reducing costs.

D. Use of Advanced Technologies
In this study, we leveraged advanced technologies such as 3D laser scanning, BIM modeling, and IoT communication protocols. By incorporating these technologies, we enhanced the accuracy, efficiency, and sustainability of the building management system.

E. Comprehensive Approach to Building Management
Our approach encompasses various aspects of building management, including environmental monitoring, drainage monitoring, power transformation and distribution, smart lighting, access systems, and fire protection. This comprehensive approach ensures that all aspects of building management are addressed, leading to more efficient and sustainable operations.

Overall, this study's novelty lies in the integration of BIM and IoT technologies, focus on old buildings, detailed implementation and results, use of advanced technologies, and comprehensive approach to building management. These aspects differentiate this study from similar studies by other researchers and contribute significantly to the field of building facility management.

5. Conclusions

We established the building facility management model using BIM and digital technology and applied it to the maintenance and management of a building. Sensors were installed in all devices to solve the problem that data could not be integrated in the previous system. Through real-time monitoring of devices, the disconnection or malfunction of the devices was prevented. The developed system monitored operations and sent out warnings or work orders for repairs, which saved costs and time. By improving data completeness, information relevance and standardization, visualization, and the management, prediction, and location of malfunctioned devices, it became easier for property managers to administrate the building-related management services than in the past. Energy-saving, convenient, comfortable, and sustainable building management was enabled by enhancing the efficiency and effectiveness of a high-rise building. Through the implementation and use of the developed system in the TWTC for one year, it was validated that BIM management can assist in building management using various sensors for various devices to monitor the operation and thereby extend the service life of the building. An inspection system was easily built by recording and integrating historical inspection results. The power consumption report created by the system is an example of how to save energy and resources effectively through IoT technology. The developed building facility management model provides an excellent reference for the future development of building management systems and related strategies to achieve the sustainable development of the economy and environment for high-rise buildings. The developed system provides an efficient and sustainable solution for managing older buildings, improving data completeness, information relevance, standardization, and visualization, leading to energy savings and better building management.

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