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RESEARCH ARTICLE

Lieyun DING, Weiguang JIANG, Cheng ZHOU

IoT sensor-based BIM system for smart safety barriers of hazardous energy in petrochemical construction

Abstract The accidental release of hazardous energy is one of the causes of construction site accidents. This risk is considerably increased during petrochemical plant construction because the project itself is complex in terms of process, equipment, and environment. In addition, a general construction safety barrier hardly isolates and controls site hazardous energy effectively. Thus, this study proposes an Internet of Things (IoT) sensor-based building information modeling (BIM) system, which can be regarded as a new smart barrier design method for hazardous energy in petrochemical construction. In this system, BIM is used to support the identification of on-site hazardous energy, whereas IoT is used to collect the location of on-site personnel in real time. A hazardous energy isolation rule is defined to enable the system to generate a smart barrier on the web terminal window, thereby ensuring the safety of on-site person. This system has been applied to a large-scale construction project in Sinopec for one year and accumulated substantial practical data, which supported the idea about the application of sensor and BIM technology in construction. The related effects of the system on hazardous energy management are also presented in this work.

Keywords IoT, BIM, smart safety barrier, hazardous energy management, petrochemical construction

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Lieyun DING, Weiguang JIANG, Cheng ZHOU (✉)
School of Civil & Hydraulic Engineering, Huazhong University of Science & Technology, Wuhan 430074, China; Hubei Engineering Research Center for Virtual, Safe and Automated Construction (ViSAC), Wuhan 430074, China
E-mail: chengzhou@hust.edu.cn

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1 Introduction

Petrochemical construction sites are places where hazardous energy is concentrated due to frequent high-risk operations, intensive technical work during the construction process, and the production process of other surrounding installations (Liu et al., 2017). The hazardous energy brings challenges to safety management on site, thereby causing production accidents and endangering public safety. Health, safety, and environment (HSE) has become the core management policy in petrochemical industries (Amir-Heidari et al., 2017) to ensure their reliability. HSE aims to assure safe production, reduce risks, prevent accidents, and achieve sustainable development. Among them, a safety barrier is the most effective way for risk and hazardous energy management (Duijm et al., 2008).

Management barriers and physical barriers, as the most common safety barriers, are widely used in construction (Winge and Albrechtsen, 2018). Management barriers generally refer to specific standards and control procedures for on-site safety and civilized construction. Such standards and procedures include worker safety training, operation guidance, and safety construction mark on site. Physical barriers, which are installed in different positions depending on the actual situation, shield the path of energy transmission. Some of these barriers, such as the field distribution box padlock, are set in the source of hazardous energy; some are set between the source of hazardous energy and personnel, such as the enclosure structure of the adjacent area; and some are set on personnel gear, such as safety helmets and belts (Sklet, 2006). However, the above barriers all have certain limitations during the implementation process. These limitations are as follows: 1) easily destroyed and crossed by personnel, 2) time-consuming and laborious installation, and 3) difficulty in initiative early warning and response for emerging risks.

A technical barrier, which refers to the perception and early warning of risks, must be set up by using information technology to isolate hazardous energy proactively

(Skibniewski, 2014). The current utilization of sensor-based technology to improve construction safety management has been a fast-developing area and a subject of interest within the engineering and academic communities (Zhang et al., 2017). For example, Zhou and Ding (2017) proposed a complete Internet of Things (IoT) barrier scheme for the partial construction of underground projects. Jo et al. (2019) designed a robust construction safety system to reduce the accidental release of mechanical energy. However, current technical barriers remain in a certain construction link and are unable to adapt to on-site changes. For the full life cycle of project management, the systematic design of safety barriers must consider the characteristics of construction activities, e.g., the site is disorderly and complex, the environment is open and harsh, and the workers behaves discursively with poor safety awareness. These features demand additional requirements for the integration of more engineering information and on-site operation information.

As a construction project lifecycle management tool, a building information modeling (BIM) system can integrate different construction information, which can effectively support the identification of on-site risk for safety management (Hossain et al., 2018). One problem needs to be solved, that is, how to guarantee the high fidelity of the BIM so that it can be implemented well. The integration of IoT and BIM complements each other, making it possible to interact with on-site and engineering information to facilitate risk management on complex sites (Tang et al., 2019). This study proposes an IoT sensor-based BIM system to address the proactive identification and dynamic control of hazardous energy in petrochemical construction. In this system, BIM is used to support the rapid identification of real-time risks on-site, and the location sensors are used to collect real-time personnel trajectory information. The state between dangerous energy and personnel is isolated by drawing an electronic fence on the system. The main contributions of this study are as follows: First, a proactive control method suitable for complex and multi-operating conditions is proposed. Second, an IoT sensor-based BIM system is proposed to achieve the interaction between sensor and BIM data. Lastly, the benefits of IoT and BIM technologies in hazardous energy management are discussed, and the application prospect and value of digital twin technology in construction site management are analyzed based on practical data.

The contents of the article are organized as follows: Section 2 reviews hazardous energy at construction sites, safety barrier management methods, and smart safety management. Section 3 presents the proposed system architecture and design. Section 4 presents system development and application. Section 5 provides the discussion and future work. Section 6 summarizes the study.

2 Hazardous energy analysis and control

2.1 Hazardous energy in construction

Gibson (1961) and Livingston et al. (2001) studied the role of production conditions, mechanical equipment, and material hazards in accidents and proposed the theory of accidental release of energy in the physical nature of accidents. They believe that an accident is an abnormal or unwanted release of energy, and various energy forms directly cause injuries. Thus, accident injuries can be prevented by controlling energy or the energy carrier, which serves as a medium for energy to reach the body (Shahrokhi and Bernard, 2010).

Energy is divided into three types, namely, point, line, and distributed energy. Energy is also found in areas such as those where people are confined (e.g., tower and tank body), semi-confined, semi-unconfined, or unconfined (McManus, 2016). The energy these areas contain is often controlled in a limited space, such as reactive fuel in a tank used for production activities, due to predictability and repeatability. At this time, hazardous energy can be isolated through management and technical means, which are prepared with short time. By contrast, construction activities are unpredictable and unrepeatable (Xu and Li, 2012), and construction sites are often outdoors and likely to be disturbed by hurricanes and other unconfined energy. Finding the energy release of construction activities often occurs at a short and chaotic state. Such hazardous energy can be hardly isolated by traditional static means.

From a victim's perspective, the skills and safety awareness of a construction worker is weaker than those in other industries (Zhang et al., 2015). Controlling the discursive behavior of construction workers can reduce the probability of safety accidents (Guo et al., 2016). In petrochemical construction, substantial hazardous energy is contained in each link of high-risk operations: Kinetic energy brought by engineering machinery lifting operation; heat and electrical energy caused by hot work; the gravitational potential energy generated by work at-height; hidden chemical energy in confined space, etc. On-site hazardous energy varies as the construction progresses. Therefore, the required means must be capable of dynamic layout and real-time response to isolate construction personnel from hazardous energy.

2.2 Safety barrier for risk control

A safety barrier is a system component that prevents, limits, or mitigates the release of hazardous elment (Duijm et al., 2004). In general, a safety barrier can be divided into three parts: Physical, technical, and administrative barriers (Sklet and Hauge, 2004). Administrative barriers may involve control of the process or the output. Hale et al. (2004) defined the four parts of a safety barrier, that is, the definition of the barrier's specification, and the detection, activation, and response mechanisms. According to their philosophy, barriers can be classified into passive, active, or procedural barriers. The nature of safety barriers, including safety barrier function, classification, parameters, and assessment, is detailed in an article by Sobral and Guedes Soares (2019).

Research on safety barriers has been applied to the real-time risk management procedures of various industries, such as technical systems in the processing and nuclear industries. For instance, at least two physical barriers are in place at all times to prevent a blowout, measure of which is called "defense in depth" in the offshore oil and gas industry (Hopkins, 2012). Safety management standards based on the energy trace and barrier analysis method have been formed in the petrochemical industry, including identifying the type of energy present in the system, energy source localization, energy flow tracking, energy blocking mechanism, and assessment of barrier failure and risk of accidental energy release (Zaranejad et al., 2016). Thus, a high-risk operation process is obtained. However, research on safety barriers in construction production is limited. Winge and Albrechtsen (2018) reviewed the most common accidents during construction and the reasons for safety barrier failure. The authors specifically mentioned that only one physical barrier was available to control a specific hazard in many construction accidents; nevertheless, systematic establishment and maintenance of barriers can contribute to accident prevention.

As a result, technical barriers are gaining extra attention. Yang and Ahn (2019) used wearable inertial measurement units to explore the relationship between the workers' behavior patterns and risks. Kanan et al. (2018) proposed a novel design for an autonomous system that monitors, localizes, and warns site laborers who work within danger zones. Sakhakarmi and Park (2019) established a tactile sensory system for the rapid perception of hazardous energy in construction. More and more smart sensors and cameras have been developed for the safety management of machinery and personnel (Rossi et al., 2019; Soltanmohammadlou et al., 2019; Wu and Zhao, 2018). The above technical barriers achieve a proactive control of hazardous energy, but only for the risk control of a certain construction stage or period. The current technical barriers cannot adapt to the changing hazardous energy during construction. The regulation of hazardous energy in an entire construction activity must be supported by an improved smart barrier.

2.3 Smart safety management

Smart safety management uses information and intelligent technology to ensure project safety in the entire life cycle. At present, IoT and BIM technologies are the most advanced methods for safety management. Zhang et al. (2017) summarized sensor-based construction safety management, covering accident forewarning system, safety route prediction and planning, integrated safety management, structural health monitoring, safety training and education, and highly dangerous operations management. Kochovski and Stankovski (2021) discussed the effects of fog computing and IoT technology in smart construction sites. A real-time alarming and monitoring active security management system based on location technology is developed and applied to site and personnel management (Li et al., 2015). Several smart equipment with IoT technology, which are similar to the self-positioning helmets proposed by Li et al. (2018), have also been developed. Given BIM's storage and simulation of engineering information integration, construction risks can be identified before the operation, thereby ensuring safety during construction (Malekitabar et al., 2016). Several scholars have conducted substantial research on risk identification methods based on BIM and security rules and applied such methods to actual fields, such as underground engineering construction (Li et al., 2018).

Researches on IoT and BIM integration are new trends, which make up for the limitations in their respective applications. BIM provides a high-fidelity operable data set capturing the as-designed building objects, properties, and spatial organization as a set of virtual assets in the preconstruction stage (Tang et al., 2019). IoT offers supplementary data of the project under construction and enhances this information set by providing real-time and recordable status from the actual construction and operations. BIM and IoT integration research is still in the nascent stage. Dave et al. (2018) described the design criteria, system architecture, workflow, and a proof of concept with potential use cases that integrate IoT with the built environment. Liu et al. (2019) realized structural fault detection of water engineering by comparing the sensor-based environment information with BIM design information. Arslan et al. (2019) proposed a system based on Bluetooth sensors and BIM to isolate people from dangerous areas indoor. Chen et al. (2021) analyzed the capabilities of IoT, BIM and Augmented Reality technology in on-site safety management and construction skills improvement. Valinejadshoubi et al. (2021) used IoT and BIM to warn the unbalanced state of somatosensory temperature in the building environment in real time during the operation and maintenance phase of the building construction. But in a challenging outdoor construction 3D environment, the benefits of the system have not been reflected. Several studies have attempted to explore how IoT sensors and BIM are inherited for the progress control of prefabrication construction (Zhong et al., 2017). In summary, most research on the IoT-based BIM system focused on the description of the underlying protocol or simple information interaction. Some engineering-oriented research also only stays in simple scenarios and a few studies have been applied to the actual construction management.

Knowing the location of hazardous energy and potential victims is important for on-site risk control. Hazardous energy is always determined by the on-site environment, construction activities, machinery, and other work conditions (Rathnayaka et al., 2012). Most of the above information can be stored in BIM and updated with the construction progress. However, the location of potential victims is often difficult to capture, thus requiring IoT sensors to track them. Based on this feature, the advantages of the IoT sensor-based BIM system comes into play, combining real engineering information with real-time operating conditions to ensure the safety of on-site personnel accurately.

3 System architecture and design

The difficulties and requirements of project safety management must be investigated thoroughly before system design to ensure that the proposed system meets the application demands in a petrochemical construction site. HSE follows the "plan, do, check, and act (PDCA)" management cycle as the general management standard of the international petrochemical industry. This study first summarizes the control process of hazardous energy in petrochemical construction, followed by the analysis of the management requirements of Sinopec, a super-large petroleum and petrochemical enterprise group in China. Figure 1 shows the definition of job scope, hazardous energy analysis, safety barrier design, management implementation, and system improvement. The management services of the system are as follows: 1) identifying and querying the location of hazardous energy and personnel on-site quickly, 2) proactively controlling the distance between unauthorized personnel and relevant energy sources in the hazardous area, and 3) recording and reporting illegal behavior of on-site personnel.

3.1 System architecture

Based on the above management ideas, the system adopted web service-based strategies for BIM and IoT integration. A multilayered architecture, which includes the perception, database, application, and action layers, was proposed to support the management of site risks and hazardous energy. Figure 2 shows the relationships at each level and what they contain. The perception and database layers are connected through Wi-Fi and local area network (LAN), whereas the database and application layers are embedded with a location algorithm and safety barrier setting rules. Meanwhile, the application and action layers are embedded with on-site management rules.

Perception layer: The perception and transmission facilities of on-site IoT are included in this layer, which is mainly used to collect on-site video (video stream) and personnel location information (3D spatial coordinates). Wi-Fi and LAN transmit the above data to the backend storage in time.

Database layer: BIM, progress, risk, on-site location, and video data are integrated in this layer. Simultaneously, relevant data are published to the web side through the interface protocol. This layer also supports the use of subsequent functions.

Application layer: Using algorithm engines, this layer performs different operational functions, including virtualization, people information management, job information management, people positioning and tracking, and hazardous area monitoring.

Action layer: Risk warning and control facilities and project management personnel are included in this layer. Site information is pushed to owners, supervisors, and workers by the web side.

3.2 Outside-in IoT network for outdoor location tracking

The outside-in network is the idea of target positioning through external base stations-wearable tags. The accuracy and timeliness of its positioning depends on the number and angle of external base station network settings. However, the complex environment of construction sites makes the establishment of outside-in IoT networking much more difficult than that for indoors. For petrochemical personnel tracking, the difficulties of on-site networking mainly lie in the comprehensive consideration of the following three points: Reliability (on-site networking should reach the farthest possible distance to cover the entire construction area), applicability (the computing server must be able to support the number of concurrent users), and economy (the cost of personnel sensor tags should be low).

This study designs the outside-in location network based on phased array radar and Bluetooth technology by combining the three targets mentioned above (Yan et al., 2017). This technology consists of a phased array antenna base station and Bluetooth tags, among which the dense

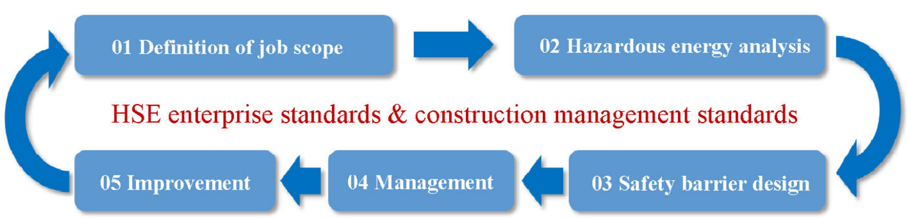


Fig. 1 Idea for control of hazardous energy.

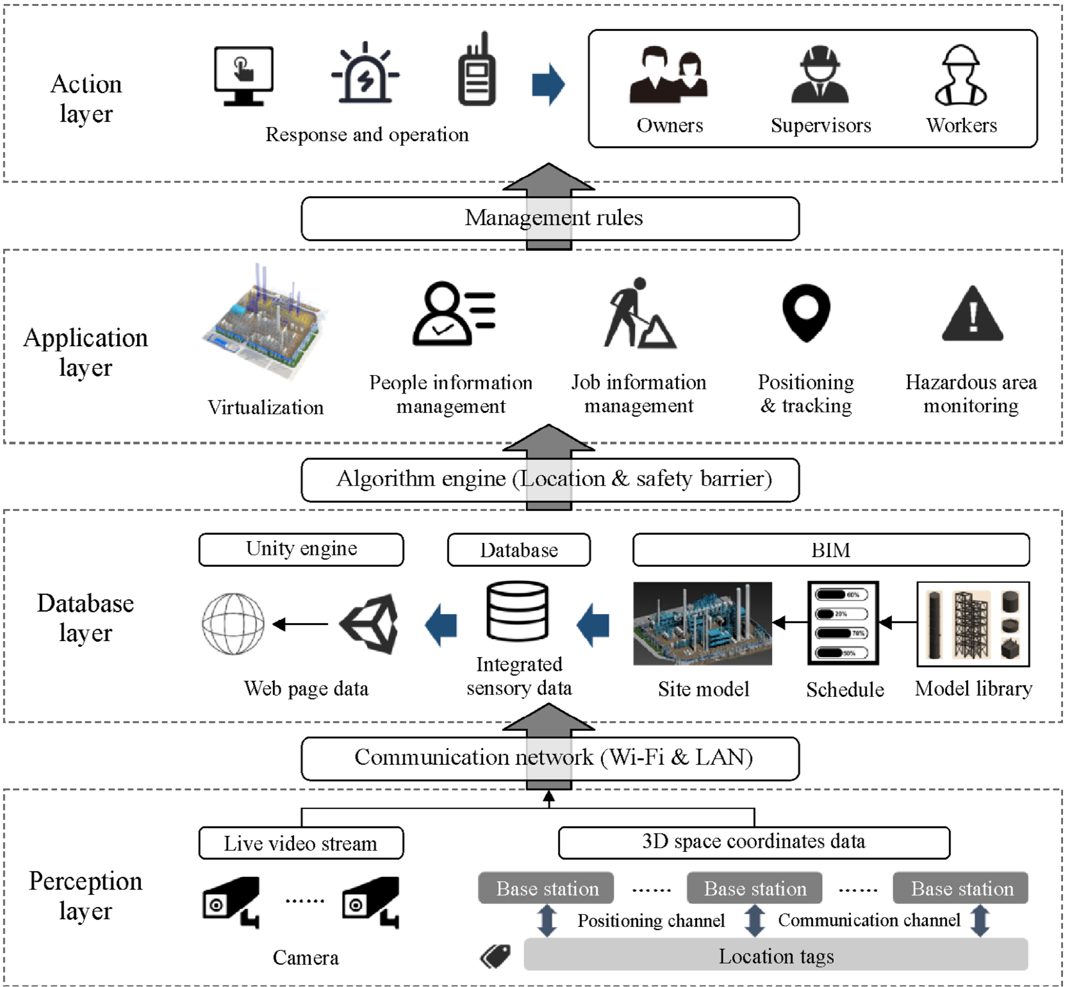


Fig. 2 Architecture of the system.

phased array antenna increases the receiving range of the tag signal. Hence, the technology is conducive to the location of large-scale outdoor scenes. Figure 3 shows that the angle-of-arrival (AoA) algorithm is adopted to reduce the interference caused by the attenuation of signal strength to the positioning accuracy of personnel for the outdoor location tracking of individual personnel. Among them, α_1 and α_2 are two azimuths, β_1 and β_2 are two elevations, and the coordinates of base stations 1 and 2 are given respectively by (x_1, y_1, z_1) and (x_2, y_2, z_2). Thus, Eq. (1) can be calculated:

$$\begin{cases} \tan\alpha_1 = \dfrac{y-y_1}{x-x_1} \\ \tan\alpha_2 = \dfrac{y_2-y}{x-x_2} \\ \cos\alpha_1 \tan\beta_1 = \dfrac{x-x_1}{z_1-z} \end{cases}. \tag{1}$$

The personnel location coordinate (x, y, z) can then be solved as shown in Eq. (2):

$$\begin{cases} x = \dfrac{y_2-y_1+\tan\alpha_1 * x_1 - \tan\alpha_2 * x_2}{\tan\alpha_1 - \tan\alpha_2} \\ y = \dfrac{\tan\alpha_1 * y_2 - \tan\alpha_2 * y_1 - \tan\alpha_1 \tan\alpha_2 * x_2 + \tan\alpha_1 \tan\alpha_2 * x_1}{\tan\alpha_1 - \tan\alpha_2} \\ z = \dfrac{y_2-y_1+\tan\alpha_2 * (x_1-x_2)}{(\tan\alpha_1 - \tan\alpha_2) * \cos\alpha_1 \tan\beta_1} \end{cases}. \tag{2}$$

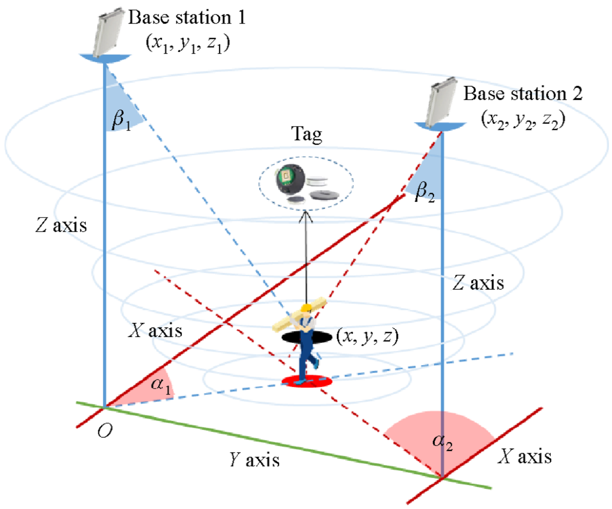


Fig. 3 AoA location principle.

In addition, a Bluetooth tag demands lower cost compared to ultra wide band (UWB) and radio frequency identification (RFID) and is convenient for field workers to carry. Figure 4 shows a schematic of the location system's on-site networking facilities and basic parameters of the base station and tag. The base station placed around the site captures the Bluetooth tag signal, and the synchronous location information is calculated in the actual application process. The LAN transmits the real-time coordinates of personnel location to the system backend.

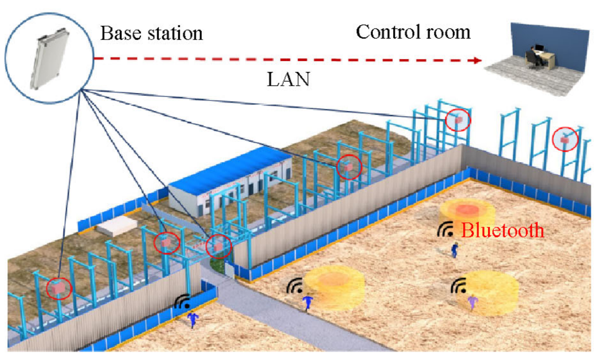
Many technical workers, such as electricians and welders, are involved in petrochemical construction. A clear definition of different operating standards and related permissions is necessary to track the hazardous energy boundary associated with different specific operations. For this reason, this system introduces the "electronic job ticket" as the main basis of personnel job information management. The main information included in the job ticket includes identification information, type of work, allowable duration of work, possible risks, location tag ID, and corresponding supervisor. Table 1 shows the different technical jobs needed to apply for the corresponding work permits according to the construction site conditions before an operation. Relevant management personnel should analyze occupational health and safety risks simultaneously. Prior to admission, each person is equipped with a tag that is a unique identification mark. Therefore, job, location, and identity information are synchronized in the system.

Table 1 Type of work and related risks

Type of work	Work permit	Safety and health risks
Electricians	Temporary power permit	Electric shock
Welders	Hot work permit	Electric spark and burn
	High-place permit	Fall
	Confined space permit	Asphyxia and poisoning
Scaffolding workers	High-place permit	Fall
	Confined space permit	Asphyxia and poisoning
Crane operators (riggers, drivers, and signal directors)	Lifting permit	Mechanical and object blow, electric shock, and collapse
Excavator drivers	Earthwork permit	Mechanical and object blow, and collapse
Gamma-ray operators	Ray detection permit	Radiation, and acute and chronic injury
	Confined space permit	Asphyxia and poisoning

3.3 BIM and safety barrier generation

The establishment of the BIM system for petrochemical construction sites reflects the on-site working condition information accurately. Prior to the establishment of the BIM, the model library of petrochemical main components, including steel structure and foundation, vertical tank foundation, vertical tank, tank, container equipment foundation, air cooler equipment, tower equipment, heat exchanger, and pipeline, is first established on the basis of Industry Foundation Classes (IFC). Furthermore, each model component is coded and associated with the construction progress information to make the model information consistent with the site information. As the



Base station

Item	Parameters
Frequency	2400–2483 MHz
Temperature	−20 °C–+70 °C
Voltage	48 V (PoE)
Protection	IP 67
Weight	400 g
Size	40 cm × 20 cm
Distance	0–80 m

Tag

Item	Parameters
Frequency	2400–2483 MHz
Temperature	−30 °C–+70 °C
Battery	600 mA
Protection	IP 57
Weight	30 g
Diameter	24 mm
Distance	0–80 m

Fig. 4 Location system networking and key parameters.

project progresses, the BIM automatically grows to achieve the most realistic display on the web side, thereby supporting the operation of site management personnel.

Similarly, the BIM site model is the basis for the identification of hazardous energy and the design of smart barriers. Figure 5 specifically describes the generation process of on-site smart barriers. First, the real-time BIM site model is used to generate the bill of quantities to start. Second, high-risk operation links and related potentially hazardous energy are obtained through job risk analysis. Third, the smart barrier of high-risk operation areas can be auto-generated independently, and the administrator can also define it independently according to the actual situation. Lastly, the generated smart barrier is presented in the BIM site model for hazardous energy management.

Table 2 shows that the above procedures are implemented in accordance with the rules of high-risk operation behavior, hazardous energy, and safety barrier formulated by the HSE management standards of petrochemical construction. Figure 6 specifically describes the prototype code of the automatic transformation of the setting parameters of hazardous energy into the safety barrier within the BIM.

The control process of the smart barrier aims to analyze personnel and real-time hazardous energy under the same system, which requires the fusion of personnel location data collected by IoT and high-risk operation areas expressed in BIM. Figure 7 shows a database framework to support the above requirements. This database contains a job and its hazardous energy data, construction site model data, personnel location data, and early warning data. Jobs and hazardous energy are associated with work, work type, risk level, safety barrier, and job track data by job ticket. The site model includes the model and schedule. Location data contain base station and tag. The database is built by the structured query language server.

3.4 System functions

With the support of the BIM, the following steps are performed successively: Encapsulating the model and related data in the unity model, adding control script, writing graphical user interface (GUI) and script, and writing network communication script. Then, the management personnel can call the system through the web side to complete the control of on-site hazardous energy. Figure 8

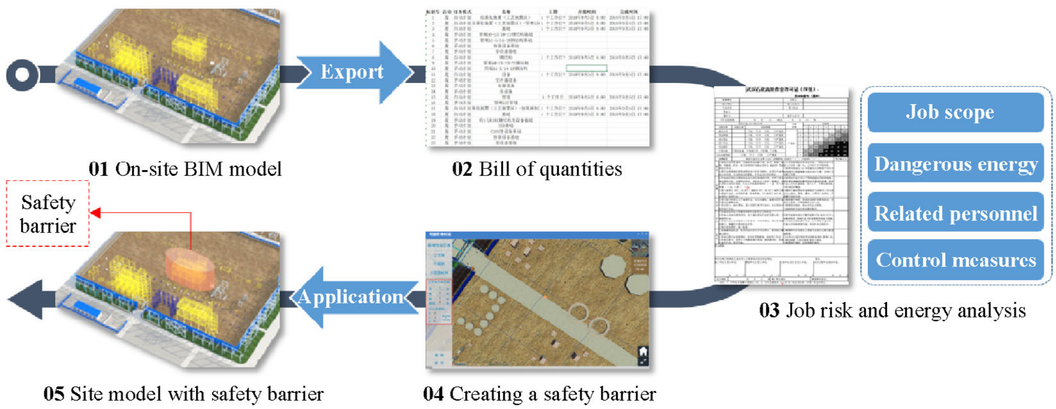


Fig. 5 Generation of dynamic safety barrier.

Table 2 Special operations and its safety barrier setting rules

Type of work	Definition	Potentially hazardous energy	Safety barrier setting rules
High-place operation	Fall height ⩾ 2 m	Gravitational potential energy	Set at the edge of the ascent
Lifting operation	Use of lifting machinery	Kinetic energy Electric energy	Set at the farthest operating radius of the crane
Earthwork operation	Anchor to depth ⩾ 0.5 m	Kinetic energy Electric energy	Set at the edge of earthwork
Hot work operation	Welding and cutting with generated spark	Thermal energy	Set at 3 m outside the operation point
Ray detection operation	Detect radioactive sources and sealed sources	Radiant energy	Set at 60 m outside the operation point
Confined space operation	Restricted exits and poor ventilation	Chemical energy Thermal energy Mechanical energy	Set at the entrance of the confined space
Temporary power operation	Use of electricity	Electric energy	Set at the perimeter of the on-site power supply box

Web Apps data

```
// Barrier generated coordinate data
String workAreaCoordinates
=result.get(i).get("f_workAreaCoordinates").toString();

// Add: zone, unit, start time, end time, risk level
JSONObject jobj = new JSONObject();
jobj = JSONObject.parseObject(workAreaCoordinates);
jobj.put("zoneType", result.get(i).get("zoneType").toString());
jobj.put("constUnit", result.get(i).get("constUnit").toString());
jobj.put("startTime", result.get(i).get("f_startTime").toString());
jobj.put("endTime", result.get(i).get("f_endTime").toString());
jobj.put("RiskScore", result.get(i).get("pbtName").toString());
……
```

BIM model with safety barrier

```
using UnityEngine;
using UnityEngine.EventSystems;
using System.Collections;
using System.Collections.Generic;
using System.IO;
using LitJson;
using System;
……
//Receive and parse web data
string editZonePath = "";
string showZonePath = "";
……
//Generate a safety barrier in zone
GameObject initCubeZones(dangerzone _dz)
……
```

Fig. 6 Prototype code for the generation of dynamic safety barrier.

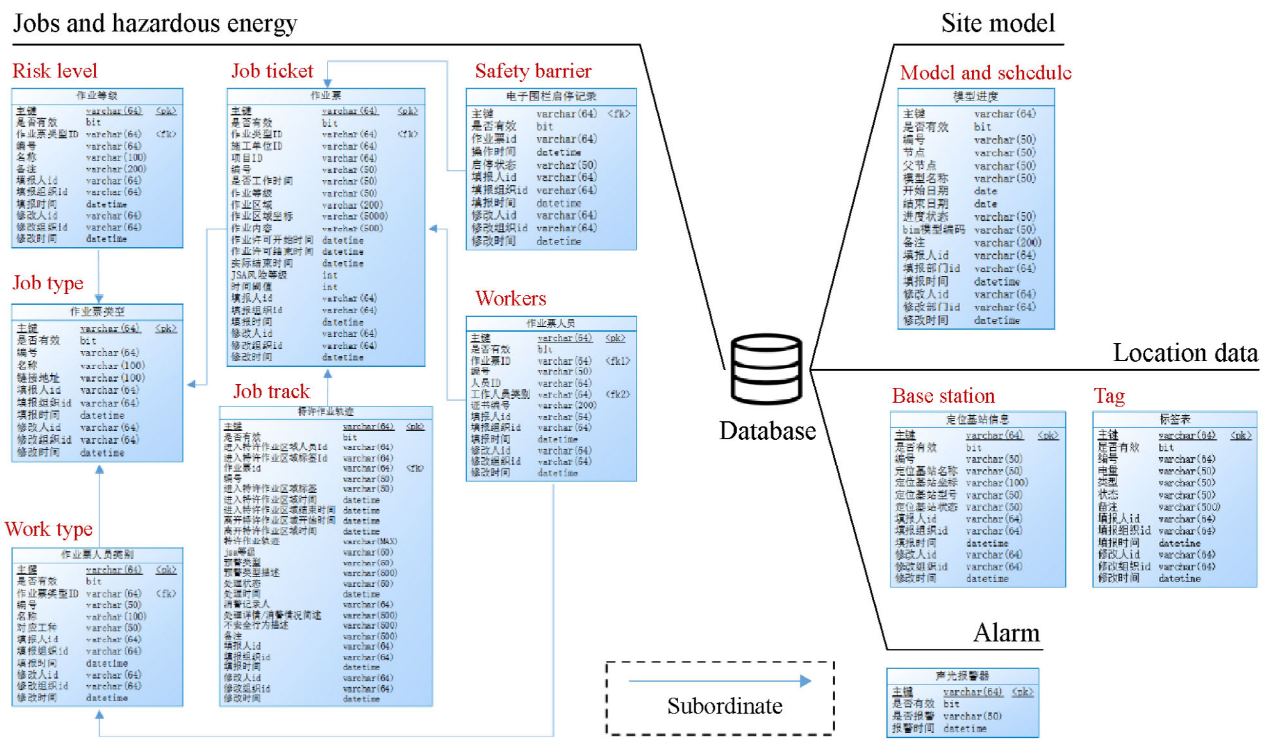


Fig. 7 System database design.

shows the operation process, in which the IoT sensor-based BIM system is supported by MyEclipse2017. The Hyper Text Markup Language (HTML), JavaScript, and Java are used to integrate and express the BIM and IoT data.

The system sets up a series of functional modules based on the efficiency objectives for project management. These modules include site virtualization, personnel information management, job information management, people location and tracking, and hazardous area monitoring. Table 3 shows the detailed function descriptions.

4 System development and application

4.1 Project overview

The global petrochemical industry is undergoing comprehensive refining and restructuring to produce clean and healthy energy. In 2017 alone, Sinopec completed the construction of 34 key projects and the renovation of 367 units. The 300000 tons/year alkylation and 700000 tons/year gas separation projects of Wuhan petrochemical

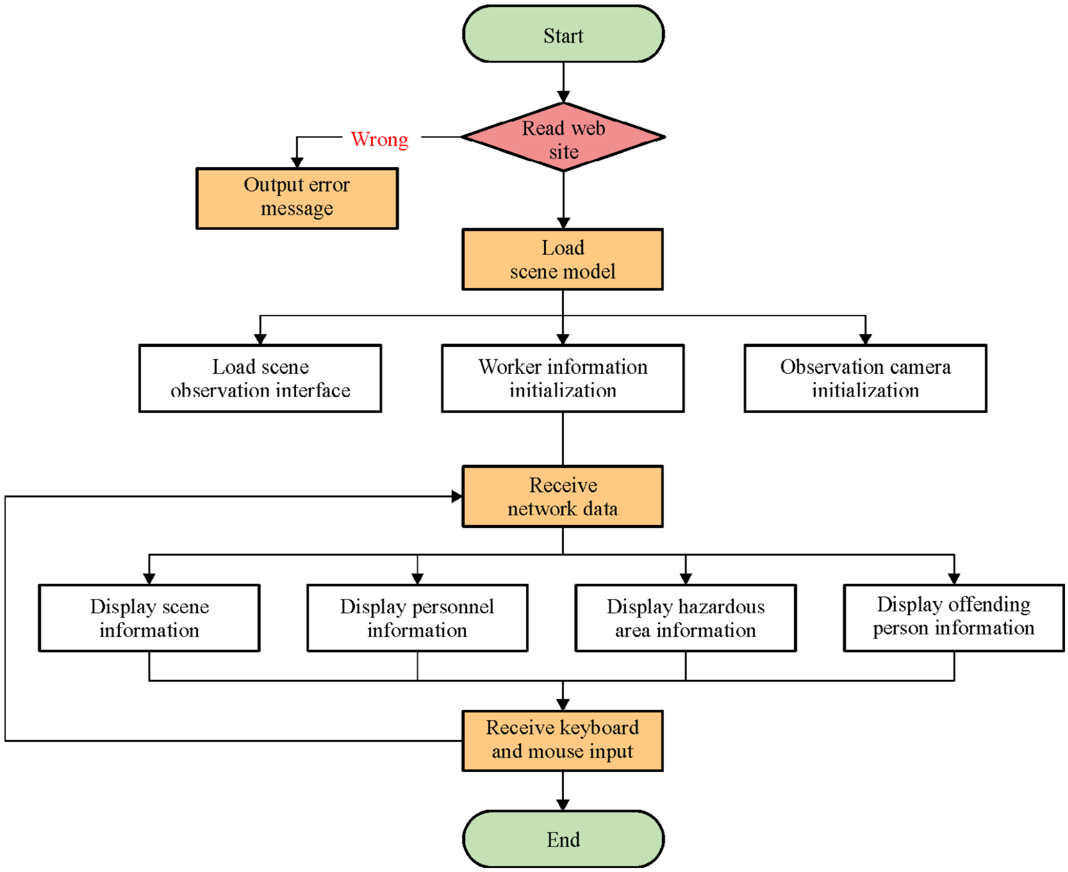


Fig. 8 System release process.

Table 3 System functions

Items	Functions
Site virtualization	• Real-time construction site model, including environment, people structure, material, etc. • Progress display: Constructions completed, under construction, and to-be constructed are shown in different colors • The interface is operable, which means it can support different perspective changes and can be scaled globally
Personnel information management	• Base information, including name, ID, photo, unit, training and qualification certificate, etc. • Evaluation information, which is used to record the unsafe behavior of people on site
Job information management	• Working area, permitted scope of operation • Working risk, hazardous energy analysis that may generate risks during operation
People location and tracking	• Real-time location, the positions of different project personnel are shown in different colors • History track query, tracks the activities of personnel on-site
Hazardous area monitoring	• Safety barrier, generates electrical barriers according to the finite energy level • Early warning and response, trespassing personnel is warned and stopped

were the key projects of Sinopec in 2018, covering a total area of 14664 m^2 (length: 156 m, width: 94 m), with a construction period of 10 months. Many kinds of potentially hazardous on-site energy were observed during the construction. These hazardous energies include the mechanical energy generated during the hoisting operation, heat and electrical energy during the welding operation, and the hidden chemical energy in confined spaces. The accidental release of such energy may not only cause injuries to people but also affect the safety of the production area and the surrounding residential area. The IoT sensor-based BIM system proposed in this study was applied in the entire process to ensure the safety of the project. Figure 9 shows the overall picture of the project and its BIM model.

4.2 System implementation process

The process of system implementation includes the dynamic establishment of a sensor network and the

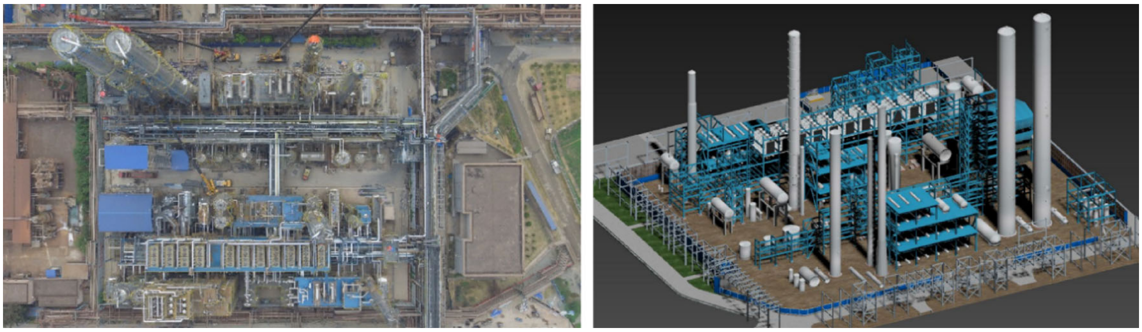


Fig. 9 Top view of the project and related BIM.

creation of the smart barrier and core management interface. These processes are all based on the results of actual management and specific operations.

4.2.1 Layout of system hardware

The layout of the outside-in location network is a process of dynamic change. According to the positioning rules of the passive phased array radar adopted in the research, the layout of the on-site outside-in network is optimized. Among them, the signal coverage test that comes with the base stations was carried out by considering the best coverage and the lowest number. Figure 10 shows that the layout process of the on-site location network is divided into three stages: Early, middle, and late stages. The early stage is the foundation construction stage, and the main structure of the site has not been formed. At this time, 7L location base stations with a strong signal range are arranged around the construction site. The middle stage is the main structure construction stage, and the on-site steel structure is gradually installed. 6L location base stations are added in the dense area of the structure for signal enhancement. The late stage is the equipment installation stage, in which the main structure of the site is basically completed. The 6L location base stations are further supplemented in several large facility installation areas to ensure the precision of location.

4.2.2 BIM with smart barrier

In the system, different smart barriers are set up to deal with the hazardous energy caused by high-risk operations. Figure 11 illustrates the process of setting up the smart barrier. The system generates the electronic job ticket of high-risk operations according to the amount of engineering work required during the day, including job ticket ID, worker's name, risk level, job position, barrier position, and job time. This information supports on-site managers to draw a smart barrier. Different drawing modes can be selected in accordance with different working modes. Among them, the crane operation generally uses a three-layer cylinder barrier, while the hot work uses the shape of a cube. The location and size of the safety barrier are also defined in this module.

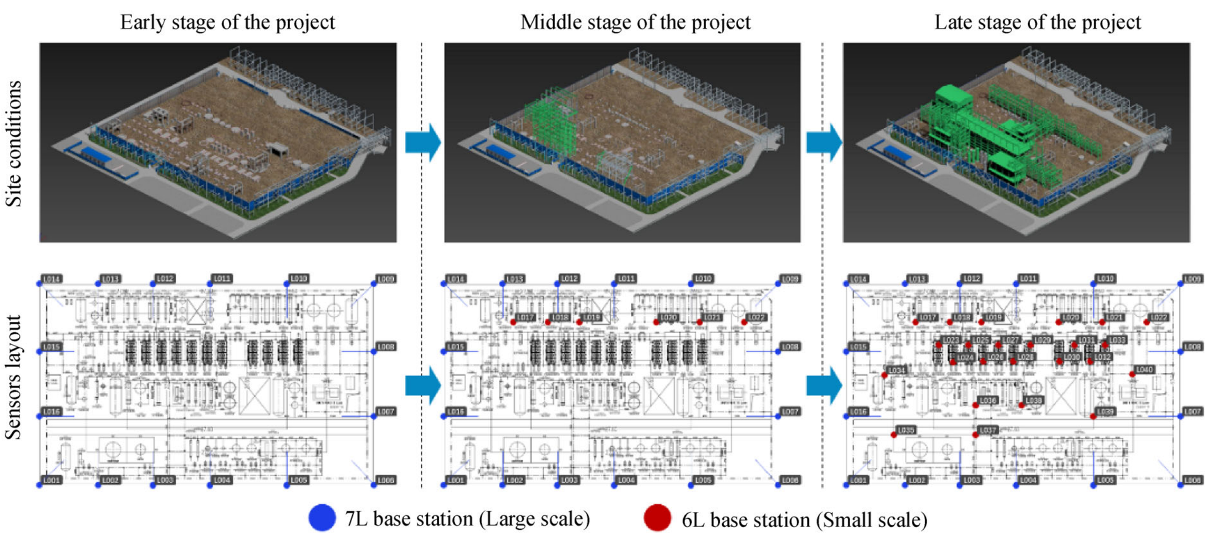


Fig. 10 Dynamic change process of on-site location network.

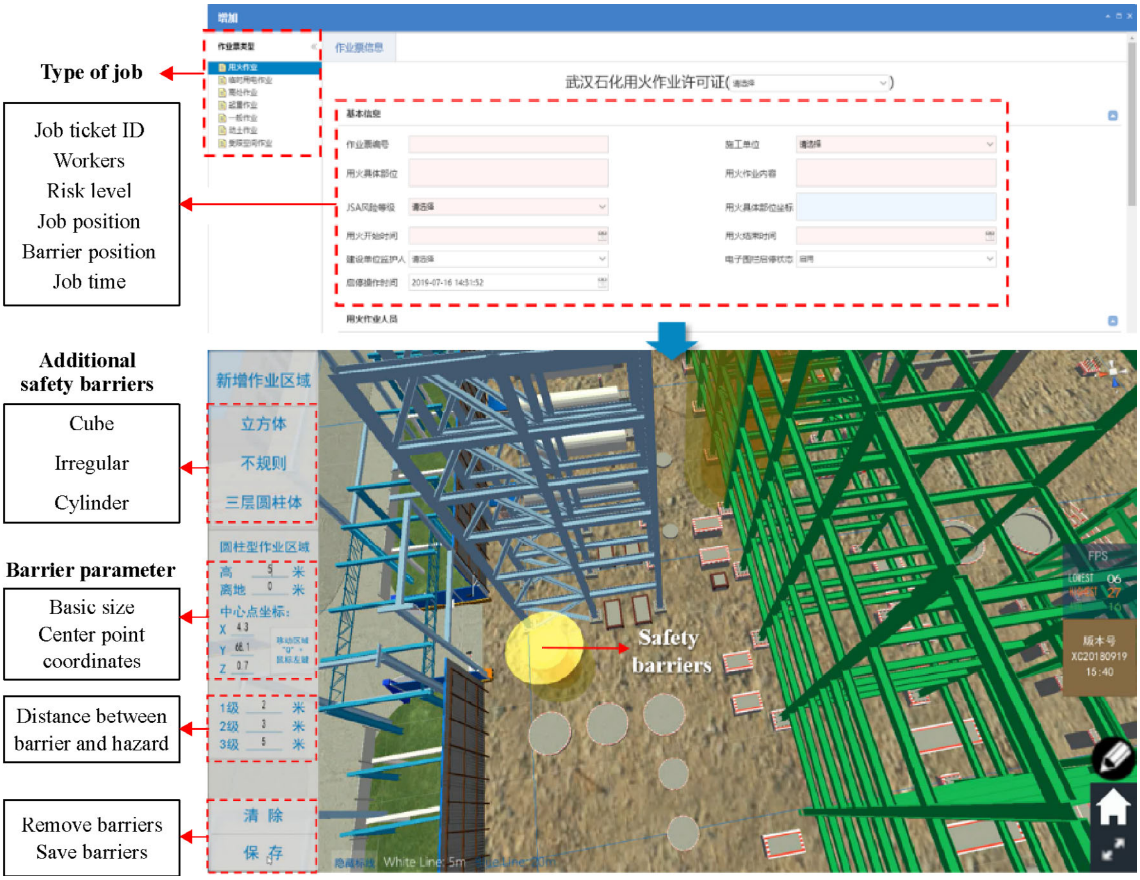


Fig. 11 Generation process of the smart barrier.

4.2.3 Management interface

IoT sensor-based BIM system forms an efficient management mode through a web page. Figure 12 shows that the information contained in various system functions is integrated, providing real-time on-site management services. The main concerns include the information and location of on-site workers, information and location of high-risk operations, real scene information, and statistical information of illegal operations. Personnel with site management authority (owner, supervisor, and construction manager) performs his respective tasks according to the above information.

The on-site smart barrier management interface should be presented. Figure 13 shows that the location information of personnel is mapped synchronously in the BIM. The interface alarms when a worker who crosses the smart barrier does not have permission to operate in this area. The identity of the person who is close to hazardous energy is immediately revealed, and the violation is immediately recorded in the system. The process of safety control is implemented through on-site supervision. The system will push specific early warning information to the mobile terminal of the supervisor around the dangerous area, and check the identity of the offender, the time of the offense, the specific behavior and the corresponding handling method.

4.3 Results for hazardous energy barrier

The system has effectively isolated hazardous energy from 167 high-risk operations and prevented 1209 people-times from trespassing in this project. Figure 14 shows the typical hazardous energy isolation interface in the system, including: 1) electrical energy control, concentrated in the field near the distribution box; 2) gravitational energy control, gathered in the foundation pit construction process; 3) kinetic energy control, which is reflected in the hoisting operation of large equipment; and 4) chemical energy control, contained in the confined space in the tank. The operating personnel appears in their permitted operating areas under the support of this system. No casualties occurred on the site during the one-year management process.

5 Discussion

The proactive isolation of on-site jobs and their related hazardous energy is the direct benefit of the proposed

Fig. 12 Management interface of the proposed system.

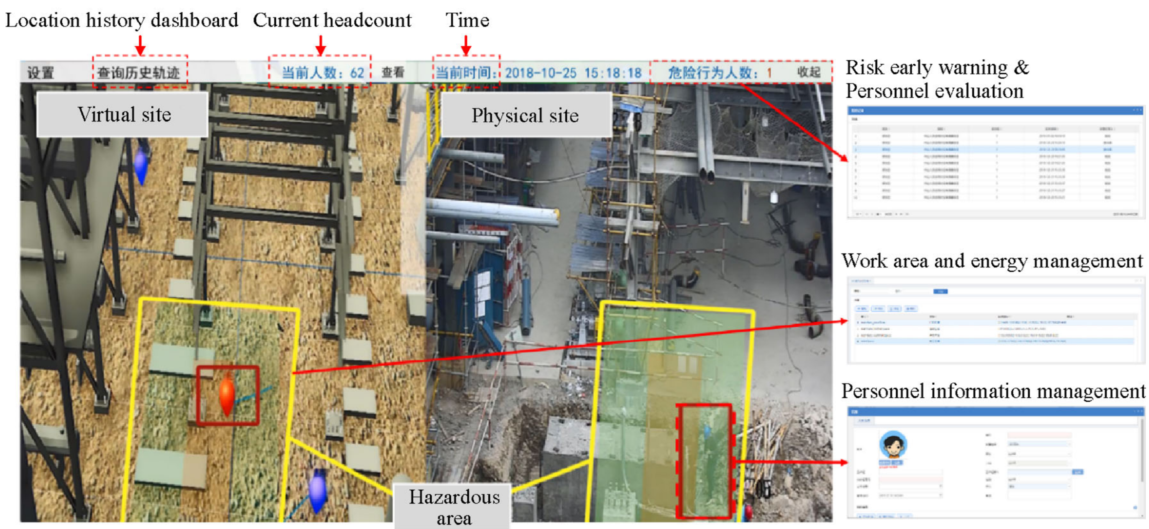


Fig. 13 Hazardous energy control interface.

system. Figure 15 shows the system's management of different technical jobs, in which high-place, lifting, and hot work are the most prone to hazardous energy in the entire construction process. The dotted line is based on the system's management of high-risk energy and its safety barriers. Although the construction tasks are very intensive, the overall operational risk is small due to the limited working space, and the corresponding safety barriers are fewer in the early stage of the project compared with that in the late stage. Given the high density of on-site operations, more cross-work behavior is observed in the late stage of the project. At this time, high-risk energy is more concentrated, and more safety barriers are available; thus, the smart barrier proposed in this study can continuously change with the progress of construction operations.

Several studies in Section 2.3 have explored the application methods of technologies on the construction site, but relatively few focused their application value with the development of IoT and BIM technology. As this work has repeatedly emphasized, the application of construction site digitization must start from the perspective of on-site management. On this basis, the actual

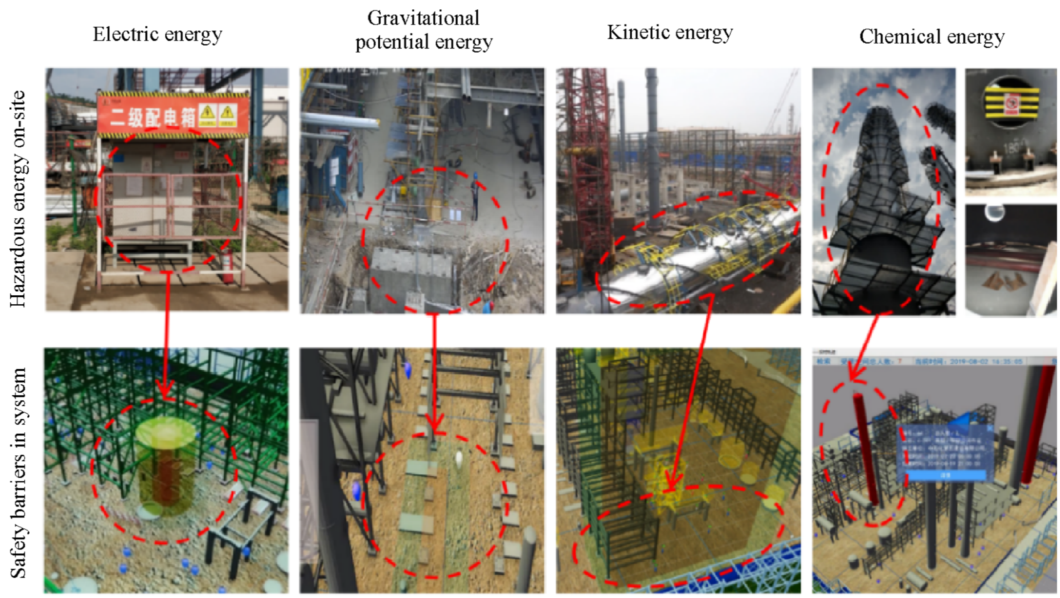


Fig. 14 Smart barriers for different hazardous energy.

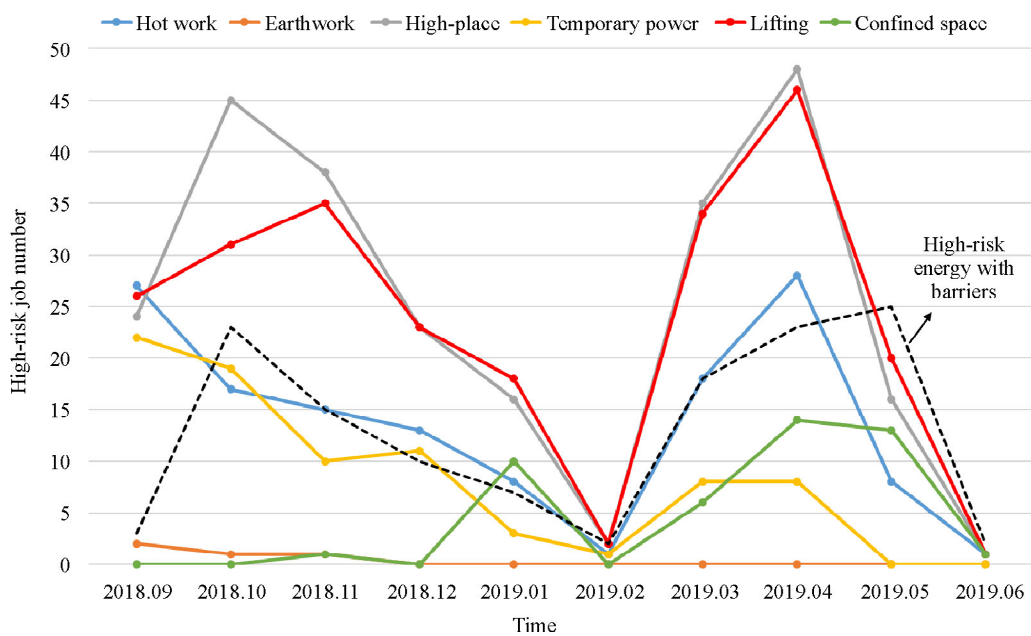


Fig. 15 Smart safety barriers for high-risk jobs.

benefits of the proposed IoT sensor-based BIM system are obtained through an interview with the owner. These benefits are closely related to the functional points proposed in this study.

1) BIM site virtualization achieves a remote and online view and identification of construction site risks and facilitates the tracking of construction progress information.

2) Personnel information management is conducive to the protection of the rights and interests of workers on site. Hence, labor disputes are reduced, and the cultivation of workers in the construction industry is promoted.

3) Job information management with electronic ticket achieves the entire-process tracking of the labor status of on-site personnel, including the working duration and location of the construction personnel and the performance record of the supervision personnel.

4) Personnel location and tracking solve the problems of on-site accident liability identification and construction quantity identification.

5) Hazardous area monitoring with the smart barrier solves the problem of proactive supervision in hazardous operation areas and liberates some supervisory workers.

With the development of digital twins, on-site safety management methods for construction sites are undergoing rapid changes. Based on the above implementation data, we believe that the prerequisite for the construction application of digital twin technology is to combine advanced management ideas. In particular, the PDCA closed-loop management system of HSE for the petrochemical industry used in the research provides a successful paradigm for the intelligent upgrade of on-site management at other construction sites. At the same time, there is still a lot of work to be carried out on the digital twin construction site in the future. 1) In theory, the management methods and models of the digital twin construction site need to be further improved and analyzed. And 2) the hazardous energy isolation proposed in this study is mainly aimed at high-risk jobs related to the worker. What can continue to be explored is the high-risk jobs related to the machinery on the digital twin construction site.

6 Conclusions

A new smart safety barrier model was proposed in this study to establish the IoT sensor-based BIM system. System architecture design, outside-in IoT network for outdoor location tracking, BIM, and safety barrier management rules were defined and described one by one. The system achieved the following management functions: Construction site virtualization, people information management, job information management, people positioning and tracking, and hazardous area monitoring. This system has been implemented for more than a year, and the case study was from large-scale engineering construction projects of Sinopec. The application results showed that the system could effectively isolate the contact between hazardous energies, such as electric, gravitational potential, kinetic, and chemical energy, and surrounding personnel. Furthermore, this study discussed the location accuracy of the outside-in IoT network in practice. Based on substantial location test data, the existing location method of "Bluetooth and phased array radar" is a good solution for most conditions, and a large signal fluctuation remains in the area with dense reinforcement. The improvement of site location in the future is discussed, especially in the use of fusion location. This study also analyzed the application of popular digital technology in smart safety management. The change of on-site management business was the premise of the implementation of digital technology, and the system proposed in this work could play a positive role for on-site safety management according to the on-site interview.

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