Industry Science and Engineering Vol. 3 No. 9, 2026

Development and Implementation of a Full-Life-Cycle Operation and Maintenance Platform for Coal Preparation Plants Based on BIM and Digital Twin Technology

Xi Yang*, Jing Yan, Zhenhua Du, Zhuang Miao, Ning Dang
Beijing NorthStar Technology Development Co., Ltd., Beijing, China
**Corresponding Author*

Abstract: To address the practical challenges commonly encountered in the operation and maintenance (O&M) stage of coal preparation plants—such as prominent data silos, fragmented asset archive management, inspection work heavily dependent on manual experience, and insufficient fault early-warning capability—this paper develops a full-life-cycle O&M platform for coal preparation plants built on a BIM-based digital foundation. The research is carried out along four dimensions: digital twin scene construction, multi-source heterogeneous data fusion, business function module development, and key algorithm implementation. The digital deliverables of BIM produced in the design and construction stages are transferred to and reused in the production and O&M stage. The platform integrates the two-dimensional/three-dimensional (2D–3D) linkage of asset archives, online condition monitoring, 3D roaming inspection, closed-loop mobile maintenance and repair management, and knowledge-graph-driven fault early warning. Engineering application shows that the platform connects the data link from design to O&M, realizes virtual–physical mapping and integrated management and control of the plant's production facilities, reduces the on-site O&M workload and the risk of unplanned downtime, and thus provides a practical reference for the digital transformation of similar coal preparation plants.

Keywords: Coal Preparation Plant; BIM; Digital Twin; 3D Visualization; Intelligent Inspection

1. Introduction

1.1 Research Background

Against the background of the "dual carbon" goals and the intelligent upgrading of the coal industry, coal preparation plants, as a key node of clean coal processing, have made digital transformation an inevitable trend of industry development [1,2]. At present, most domestic coal preparation plants have completed basic automation upgrading, and PLC (Programmable Logic Controller) control systems, various sensor monitoring devices and video surveillance systems have been widely deployed; however, automation and informatization remain disconnected. A large number of engineering drawings, equipment ledgers and maintenance histories are still stored in paper documents or in scattered and independent systems, and there is a lack of unified data exchange interfaces between different business systems, which forms a typical data silo [3,4].

At the operational level, inspection, defect handling and maintenance planning rely heavily on the on-site experience of O&M personnel; fault handling is dominated by post-failure repair, lacking prediction means based on historical data [5]. Once an abnormality occurs in a key production facility, it can easily cause a plant-wide shutdown and considerable economic loss.

BIM (Building Information Modeling) and digital twin technologies provide a feasible path to solve the above problems. BIM carries the digital information of the whole engineering life cycle, while the digital twin realizes the real-time mapping between the physical plant and the virtual scene [6]; the combination of the two can extend the digital assets formed in the construction stage to serve production and O&M. At present, BIM in coal preparation plants is mostly concentrated in the design and construction stages, and the BIM deliverables after completion and handover are often left idle [7], failing to fully empower the later production and O&M business.

1.2 Research Status

Many domestic scholars have carried out research on 3D platforms for intelligent coal preparation plants. Some studies completed the framework design of a coal preparation information model and realized basic visual display [8]; other studies explored technologies around PLC data acquisition and intelligent inspection of coal preparation plants [9,10]. However, existing solutions generally have two shortcomings. First, most platforms focus on production monitoring and display and lack the capability of a full-life-cycle business closed loop, so BIM design deliverables are not closely integrated with maintenance and ledger business. Second, the underlying key technologies, such as standardized access to multi-source heterogeneous systems, roaming inspection path control and fault knowledge mining, are not sufficiently elaborated [11,12].

This paper addresses the actual production and O&M business of coal preparation plants and studies a full-life-cycle O&M platform driven by BIM + digital twin. The main research contents are as follows:

1) A digital twin foundation for coal preparation plants is constructed, which realizes the reverse completion and lightweight processing of as-built BIM models, and a unified facility code is established to associate models with business data;

2) Multi-source heterogeneous data fusion technology for coal preparation plants is studied, a multi-mode acquisition scheme is designed, and the standardized access of PLC, sensors, video and ledger documents is completed;

3) The business function system of the platform is designed, realizing 2D-3D linkage of asset archives, online condition monitoring, 3D roaming inspection, closed-loop mobile maintenance and repair, and knowledge-graph-based fault early warning;

4) A path control algorithm for 3D roaming inspection is implemented, and the practical application effect of the whole platform in a real coal preparation plant is verified.

2. Overall Architecture Design of the Platform

2.1 Overall Design Concept

Following the principle of "BIM as the foundation, data as the core and business as the orientation", the platform bridges the data gap among design, construction and O&M of the coal preparation plant, migrates the digital delivery assets of the construction period to the production stage, and builds a digital twin O&M system with virtual-physical mapping. A unified facility code serves as the link between models and the business database, supporting various O&M applications upwards and connecting on-site sensing hardware and existing business systems downwards, so as to achieve integrated management and control of asset-monitoring-inspection-maintenance-early warning for the coal preparation plant.

2.2 Layered Architecture Design

From bottom to top, the platform is divided into five layers: the sensing access layer, the data fusion layer, the digital twin foundation layer, the business application layer, and the presentation and interaction layer [13], as shown in Figure 1.

1) Sensing access layer: it includes field hardware such as the PLC control system of the coal preparation plant, temperature and vibration sensors, gas monitoring instruments, level gauges, belt scales and cameras, and is responsible for acquiring raw working condition, video and environmental signals. It is the data source of the whole platform.

2) Data fusion layer: it realizes the acquisition, parsing, cleaning and storage of multi-source heterogeneous data and is compatible with four modes, namely OPC (Open Platform Communications) real-time acquisition, FTP (File Transfer Protocol) file acquisition, database extraction and manual entry. It completes streaming and batch data fusion and outputs standardized data sets, providing data support for the twin scene and business modules above.

3) Digital twin foundation layer: it includes the BIM model repository, model lightweight processing, 3D engine services and coding mapping services [14]. It completes the 1:1 digital twin scene construction of the plant area and realizes 3D scene rendering, model retrieval and positioning, and 2D-3D linkage, which is the basis of platform visualization.

4) Business application layer: it encapsulates five business modules, namely asset archive management, online monitoring of production operation, intelligent inspection management, maintenance and repair work order management, and knowledge-graph-based fault early warning, implementing the full-life-cycle O&M business

logic of the coal preparation plant.

5) Presentation and interaction layer: it includes the Web 3D management terminal and the mobile inspection APP. Managers complete platform configuration and global monitoring through the Web terminal, while field operators use the mobile terminal to carry out code-scanning inspection, defect reporting and work order execution.

2.3 Business Process of the Platform

The complete business process is as follows: (1) the design/as-built BIM model is processed and imported into the twin foundation, and a unique facility code is established; (2) the sensing access layer collects various field data, which are standardized by the data fusion layer; (3) the data are bound to 3D model objects through code mapping; (4) the business application layer invokes model and data resources to carry out archive query, condition monitoring, inspection task issuing, work order circulation and fault early warning; (5) human-computer interaction is completed on the Web terminal and the mobile terminal respectively, forming a closed loop of "acquisition-fusion-mapping-business-feedback".

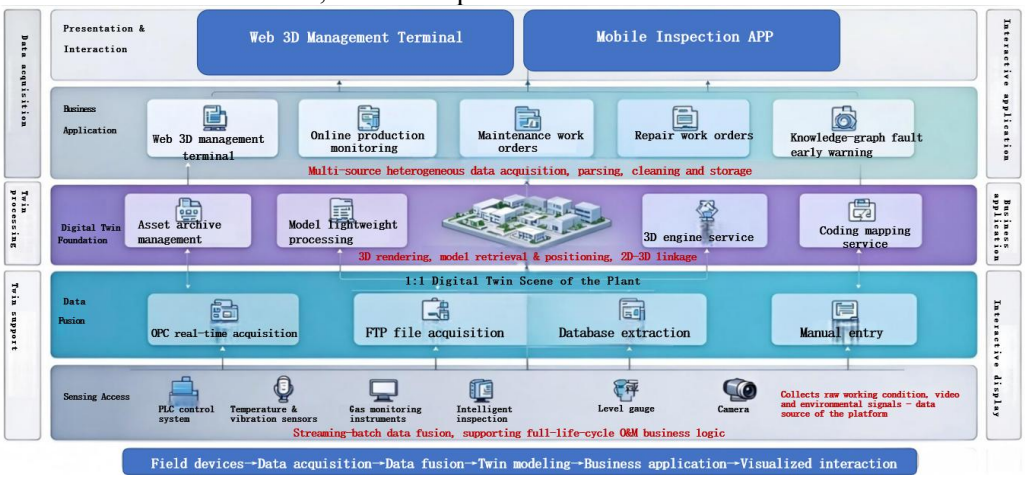


Figure 1. Platform Architecture

3. Implementation of Key Technologies

3.1 Construction of the BIM Digital Twin Foundation for Coal Preparation Plants

Two practical scenarios are considered: for coal preparation plants that already have complete as-built BIM deliverables, the models of the construction stage are directly reused; for operating coal preparation plants lacking as-built BIM models, 3D laser scanning combined with UAV oblique photography is used for reverse digital reconstruction [15]. The modeling granularity is refined to the component level, fully preserving the geometric shape, spatial position, topological relations and engineering attributes of the facilities.

Lightweight processing is applied to the original BIM model to reduce rendering pressure. Each production facility is assigned a globally unique facility code [16], which acts as a bridge to bind 3D model objects one-to-one with ledger, monitoring and maintenance records in the database, supporting the subsequent retrieval, linkage and data mounting business.

3.2 Multi-source Heterogeneous Production Data Fusion Technology

Coal preparation plants simultaneously have streaming real-time monitoring data and batch historical business data, and the system protocols and formats differ greatly. This paper adopts a streaming-batch fusion processing scheme.

1) Flume-based hierarchical acquisition architecture: distributed multi-source data are decoupled hierarchically, and a grouped two-level hash load balancing strategy is designed to make up for the deficiency of native Flume load balancing and to improve the transmission stability of large data volumes [17].

2) PLC real-time acquisition based on the OPC protocol: a C/S (Client/Server) architecture OPC acquisition client is built to connect with the field PLC server, uniformly acquiring the real-time working condition signals of instruments and equipment.

3) Multi-mode adaptive acquisition: all raw data are parsed and cleaned to form standardized data sets, which are stored for the invocation of upper-layer business.

3.3 Path Control Algorithm for 3D Roaming Inspection

3D roaming is the core of virtual inspection and needs to solve the problems of flight path generation, smooth view adjustment and attitude switching at inflection points [18].

1) Flight path generation: inspection path key points are added in the 3D interactive interface, and the spatial coordinates, elevation, pitch angle and azimuth angle of each point are recorded; adjacent key points form a spatial path vector, from which the camera attitude parameters are solved.

2) Frame-by-frame camera control: to avoid climbing and model penetration during the flight, the elevation logic is locked throughout the whole process and the camera position is updated frame by frame.

3) Smooth switching at inflection points: a time-difference discrimination mechanism is adopted instead of judging attitude switching by displacement distance. The theoretical total time t_1 for the camera to reach an inflection point is compared with the actual flight time t_2, and a threshold $\Delta t = 10$ ms is set. When $|t_1 - t_2| < \Delta t$, the smooth jump of the camera attitude is completed, avoiding path disorder during high-speed roaming.

With this algorithm, automatic roaming along a preset route can be realized. During roaming, the monitoring data and video streams of the facilities along the route are retrieved synchronously, thus completing virtual inspection at the dispatching end.

4. Design of Core Business Functions of the Platform

4.1 2D-3D Linkage Management of Asset Archives

Based on the digital twin foundation and the unified coding system, digital archive management of coal preparation plant assets is realized, as shown in Figure 2.

1) Digital archive query: by clicking a facility model in the 3D scene, PDF drawings, factory documents and installation documents can be retrieved directly, replacing the traditional paper archive cabinet;

2) 2D-3D linkage of P&ID (Piping and Instrumentation Diagram) process drawings: the 2D process flow diagram and the 3D model are located by bidirectional jumping, so that pipelines and process topology can be quickly clarified;

3) Comprehensive asset information view: a pop-up window displays facility ledgers, technical parameters, suppliers and all historical maintenance defect records in a centralized way;

4) Model retrieval and positioning: through the directory tree plus keyword retrieval, the retrieval results are highlighted and positioned in the 3D scene, so that target facilities can be located quickly.

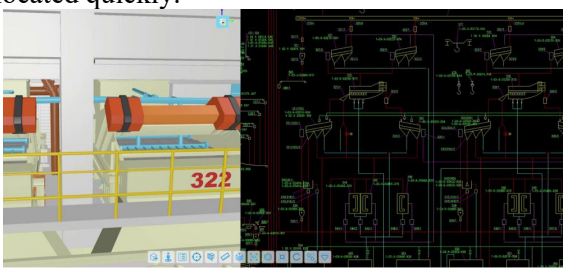


Figure 2. 2D-3D Linkage of Asset Archives

4.2 Online Monitoring of Production and Operating Status

Nine categories of field business data are mounted onto 3D BIM model objects, realizing the synchronous mirroring of the physical plant conditions in the virtual scene, as shown in Figure 3. These data include temperature and vibration monitoring, storage level, belt scale output, valve status, instrument readings, gas environment monitoring, ash meter data and video surveillance.

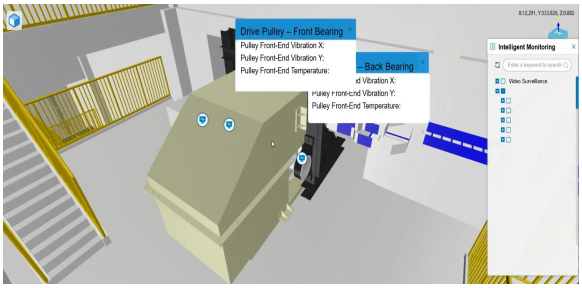


Figure 3. Schematic Diagram of Equipment Monitoring Status

4.3 3D Visualized Intelligent Inspection

The platform supports both virtual roaming inspection at the dispatching end and code-scanning inspection on the mobile terminal in the field.

1) 3D roaming inspection: inspection routes are preconfigured, and the system automatically roams along the route and automatically retrieves the monitoring data and surveillance video along the way, completing virtual inspection without leaving the office;

2) Mobile terminal field inspection: field personnel scan the QR codes of facilities to check in for inspection, take photos and report problems when defects are found, and the data are transmitted back to the background in real time; the platform displays the inspection trajectory of personnel in the 3D scene to supervise task execution and reduce missed inspections.

4.4 Closed-loop Management of Maintenance and Repair Work Orders

The whole process of maintenance planning, work order dispatching, on-site handling, acceptance and archiving is closed online. Managers create periodic maintenance plans or temporary defect tasks on the platform, and the system automatically generates maintenance work orders and issues them to the mobile terminal; maintenance personnel return the results after completing the on-site handling, and the whole process of the work order is traceable, which improves the efficiency of defect elimination.

4.5 Knowledge-Graph-Driven Fault Early Warning

The platform continuously accumulates a large number of historical fault records and maintenance work order data, builds a fault knowledge graph of coal preparation plant facilities, mines the correlation between fault features, and carries out fault prediction for key production facilities [19]. When monitoring indicators become abnormal, the platform actively issues an early warning and prompts O&M personnel to carry out maintenance in advance, reducing the risk of unexpected shutdown.

5. Engineering Application Analysis

The BIM + digital twin full-life-cycle O&M platform developed in this paper has been applied in a large coal preparation plant. The BIM as-built digital delivery results of the plant were reused to complete the construction of the digital twin scene, and the whole-plant PLC system, various sensors and video surveillance were connected, with the five business modules fully deployed.

From the perspective of the actual application effect, the following results have been achieved:

1) Improved archive query efficiency: drawings, ledgers and maintenance records are all bound to 3D facilities, so that data query is shortened from more than ten minutes to several seconds, and the 2D-3D drawing linkage reduces the difficulty of drawing recognition for O&M personnel;

2) More intuitive condition perception: various working condition and environmental monitoring data are visualized in the 3D scene, abnormal indicators are highlighted and alarmed, and combined with video images, the dispatching center can intuitively grasp the production status of the whole plant;

3) Diversified inspection modes: both remote virtual roaming inspection and on-site mobile code-scanning inspection are supported, and inspection trajectories are traceable, effectively reducing missed inspections;

4) Closed-loop control of the maintenance business: maintenance work orders circulate online throughout the whole process, and the O&M process is fully traceable; relying on the knowledge graph, advance fault warning is realized for some key facilities, reducing the probability of unplanned shutdown.

Practice shows that the platform fully releases the value of BIM digital delivery assets, breaks the data barrier between design and O&M, reduces the dependence of O&M on personnel experience, and improves the standardization and intelligence level of coal preparation plant O&M.

6. Conclusion and Prospect

To address the problems of data fragmentation, fragmented archives, traditional inspection means and weak fault early warning in the O&M stage of coal preparation plants, this paper designs a five-layer BIM + digital twin full-life-cycle O&M platform. The key technologies of digital twin foundation construction, the 3D roaming inspection algorithm and multi-source heterogeneous data fusion are studied; the business modules of 2D-3D asset archive management, online condition monitoring, intelligent inspection, work order closed loop and knowledge-graph fault early warning are developed; and engineering case verification is completed.

The results show that the platform can effectively reuse the BIM deliverables of the construction period in the production and O&M stage, realize the integrated management and control of facility assets, monitoring, inspection and maintenance business of coal preparation

plants, and reduce the loss caused by unplanned shutdown, which has reference value for the digital upgrading of similar coal preparation plants.

Future work will further expand the fault sample data set and iteratively optimize the knowledge-graph fault prediction model to improve the accuracy of fault early warning. In addition, the deep integration between the platform and the production dispatching system of coal preparation plants will be explored to further expand the business boundary of the digital twin platform.

References

[1] Cheng Hongzhi. Reflections on the development of coal preparation technology under the strategic goals of carbon peak and carbon neutrality. Coal Preparation Technology, 2022, 50(5): 1-6.

[2] Cheng Zizhao, Ma Jian. Research on high-quality development of coal preparation under the background of “dual carbon”. China Coal, 2022, 48(7): 10-16.

[3] Fang Qian, Zhang Xiaoxia, Wang Lin, et al. Research, practice and application of key technologies for big data governance in intelligent coal mines. Industry and Mine Automation, 2023, 49(5): 37-45, 73.

[4] Wan Maoquan, Li Hao, Wang Hao. Research and application of cross-system unified data service for coal mines based on industrial internet platform. Industry and Mine Automation, 2025, 51(3): 96-104.

[5] Kuang Yali, Wang Zhangguo, Wang Guanghui, et al. Research progress on key technologies for intelligent construction of coal preparation plants . Coal Preparation Technology, 2023, 51(6): 24-33.

[6] Zhang Fan, Ge Shirong, Li Chuang. Review on digital twin technology of smart mines. Coal Science and Technology, 2020, 48(7): 168-176.

[7] Guo Qinghua, Wei Zhongkuan, Zhang Shusen, et al. Design of 3D visual management platform for intelligent coal preparation plant based on coal preparation information model . Industry and Mine Automation, 2022, 48(11): 54-62.

[8] Liu Yuemu, Zhai Qiangshun, Qiao Jiang, et al. Research on the construction of a 3D visualization twin system in Qinglongsi coal washing plant. Coal Engineering, 2024, 56(8): 190-196.

[9] Jiang Zhanglei, Li Nianxue, Li Yunpeng, et al. Research on construction technology of multi-source heterogeneous industrial data collaborative management information model based on OPC UA. Machine Tool & Hydraulics, 2024, 52(22): 8-15.

[10] Zhao Xinglei, Zhang Xinyuan. Application of a quadruped bionic inspection robot in Shangwan coal preparation plant. Clean Coal Technology, 2023(S1): 185-188.

[11] Gao Jianchuan, Wang Ranfeng. Challenges and reflections on the intelligent construction of coal preparation plants. Intelligent Mine, 2024(9).

[12] Kuang Yali, Wang Zhangguo, Wang Guanghui, et al. Research progress on key technologies for intelligent construction of coal preparation plants . Coal Preparation Technology, 2023, 51(6): 24-33.

[13] Wan Maoquan, Li Hao, Wang Hao. Research and application of cross-system unified data service for coal mines based on industrial internet platform. Industry and Mine Automation, 2025, 51(3): 96-104.

[14] Zhang Shaojin, Zhang Huiyu, Wang Xiaojing. Review on BIM lightweight management technology. Information Technology in Civil Engineering and Architecture, 2023, 15(6): 117-122.

[15] Tan Jinshi, Zu Weiguo, Liu Li. Method for constructing 3D building models through air-ground collaboration of laser scanning and oblique photography. Applied Laser, 2023, 43(7): 107-115.

[16] Zhang Shaojin, Zhang Huiyu, Wang Xiaojing. Review on BIM lightweight management technology. Information Technology in Civil Engineering and Architecture, 2023, 15(6): 117-122.

[17] Wan Maoquan, Li Hao, Wang Hao. Research and application of cross-system unified data service for coal mines based on industrial internet platform. Industry and Mine Automation, 2025, 51(3): 96-104.

[18] Ren Wei. Inspection system for fully mechanized mining face based on SLAM and virtual realit. Industry and Mine Automation, 2023, 49(5): 59-65.

[19] Cai Anjiang, Zhang Yan, Ren Zhigang. Construction of fault knowledge graph for fully mechanized coal mining equipment. Industry and Mine Automation, 2023, 49(5): 46-51.