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Development of Intelligent Storage and Logistics Management System for Thermal Power Plant

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Abstract: As the core industry of energy supply, the efficiency of storage and logistics management of thermal power plant has a direct impact on the safety, economy and sustainability of power generation. At present, the traditional thermal power plant warehousing and logistics system is faced with decentralized management, information lag, high dependence on manual and insufficient cost control, which cannot meet the needs of modern management. The in-depth application of Internet of Things (IoT) technology provides technical support for the digital upgrade of warehousing and logistics system, but there are still challenges in data integration depth, prediction model accuracy and adaptability to complex environment. The intelligent warehouse and logistics management system developed in this study for thermal power plants integrates IoT, AI, and automation technologies to create a smart management platform that covers full lifecycle tracking of material information, automated warehouse scheduling, intelligent logistics path optimization, and multidimensional data analysis. By deploying RFID tags, smart sensor terminals, and AGV logistics equipment, combined with recursive neural networks and reinforcement learning algorithms, the system achieves real-time material status monitoring, precise inventory demand forecasting, and dynamic optimization of transportation routes.

Keyword: Thermal power plant; Intelligent storage; Logistics management system; Internet of Things (IoT) technology

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1. Introduction

As an important basic industry of energy supply, the efficiency of storage and logistics management of thermal power plant directly affects the safety, economy and sustainability of power generation. At present, the traditional thermal power plant storage and logistics system still has the problems of decentralized management, lagging information, high dependence on manual and insufficient cost control. With the expansion of power generation capacity and heightened environmental protection requirements, traditional warehousing models have become inadequate for modern management needs. There is an urgent need to optimize the entire process through intelligent solutions. The deep integration of IoT technology in material management for thermal power engineering projects provides technical support for the digital transformation of warehousing and logistics systems [1]. For example, the real-time monitoring and tracking system based on the IoT can effectively solve the problem of information asymmetry in the circulation of materials, but the existing system still faces challenges such as insufficient depth of data integration and the need to improve the accuracy of prediction model.

2. System development plan design

2.1. Functional module design

The three-dimensional intelligent evolution of the warehouse management module employs four-dimensional dynamic inventory modeling technology, deeply integrating automated storage and retrieval (AS/RS) with IoT as follows:

(1) Spatial perception revolution: Deploy UWB (Ultra-Wideband) positioning base stations (± 5cm accuracy) on each shelf layer, combined with RFID tags (920 MHz frequency, 8 m read range) to establish a 3D material coordinate system. When coal stacker cranes perform storage tasks, the system calibrates cargo position deviations in real time (0.3 mm error compensation algorithm precision), resolving the ± 50cm error issue of traditional barcode positioning;

(2) Multimodal perception matrix: The shelf unit integrates temperature-humidity sensors (± 0.5°C accuracy), pressure sensors (10 t range), and dust concentration meters (0–1000mg/m^3), transmitting data wirelessly to edge computing nodes via LoRaWAN. When detecting coal pile spontaneous combustion risks (temperature > 60°C and CO concentration > 50ppm), the system automatically activates nitrogen gas fire suppression devices [2,3];

(3) Intelligent replenishment engine: This system calculates dynamic safety stock using Prophet algorithm-based time series forecasting, integrating supplier lead times (LTD) and demand fluctuation coefficient (σ = 0.18) to generate precise replenishment instructions. At Huaneng Rizhao Power Plant, this strategy reduced spare parts shortage rate from 12% to 0.7% while boosting inventory turnover by 41%.

2.2. Space-time collaborative optimization of logistics scheduling module

In view of the complexity of power material transportation, a multi-level dynamic optimization system is constructed as outlined:

(1) Path planning core: The system employs an enhanced A* algorithm integrated with real-time traffic data (obtained via Gaode API for road condition delays) and incorporates risk weighting factors (road gradient, bridge load limits). When transporting oversized equipment like transformers, it automatically avoids sections with gradients exceeding 3%, reducing the standard deviation of transportation time fluctuations from 45 minutes to 12 minutes;

(2) Safety verification closed loop: Implement triple protection for the transportation of hazardous chemicals:

  (i) RFID in-vehicle system with electronic seal linkage (seal break alarm with < 3-second delay);

  (ii) The X-ray scanner (160 kV energy) automatically detects packaging damage with a false detection rate of < 0.2%;

  (iii) The Raman spectrometer (resolution 2cm^{-1}) detects leakage substances in real time (response time < 8 seconds);

(3) Abnormal response mechanism: When the GIS system detects vehicle deviation from the planned route

(deviation > 500m) or sudden braking (acceleration > 0.5g), it immediately triggers a Level 3 response:

(i) Level 1: Send correction commands to the driver via dual 4G/5G links;

(ii) Level 2: Alert the nearest emergency response team (with positioning accuracy < 10m);

(iii) Level 3: Activate the backup transport plan (path re-planning takes less than 15 seconds).

In the field test of Yue Dian Zhuhai Power Plant, the system achieves results as follows:

(1) The efficiency of warehousing operation is increased by 3.2 times (the daily processing capacity is increased from 800 tons to 2560 tons);

(2) Transportation cost reduced by 27% (annual saving of 4.3 million Chinese Yuan through path optimization);

(3) Zero safety accidents (zero violations in dangerous goods transportation in 2023).

2.2.3. Database design

The database design of this system adopts the combination of hierarchical architecture and normalization principle to ensure the efficiency and scalability of data storage. The core data tables include material information, inventory management, inbound/outbound records, supplier information, and logistics equipment. Each table establishes a many-to-many relationship through primary and foreign keys. The material information table contains fields such as the unique identifier, name, specification and model, measurement unit, storage location, safety stock threshold, and classification code. The classification code uses a hierarchical structure to support multi-level classification management. The inventory management table uses the material ID as a foreign key to link to the material information table, with extended fields including inventory quantity, batch number, production date, and expiration date. The version number field enables inventory snapshot functionality, supporting historical data traceability and version comparison. The inventory record form contains operation type, operation time, operator, quantity, and associated business document number. The business document number acts as a foreign key pointing to purchase order, material requisition, transfer order, and other business forms, forming a complete business loop.

To meet real-time query and statistical requirements, the database adopts a cluster deployment strategy. The core business tables are distributed storage through hash sharding. The sharding key is selected by the combination of material classification code and storage area code to ensure the locality of operations and query efficiency of similar materials. For frequently queried material inventory status, establish commonly used statistical indicators for materialized view pre-calculations, and set triggers to synchronize view data with source tables. The data tables are linked using third normal form design, which avoids redundant storage while optimizing the performance of multi-table join queries through database indexing [4]. The supplier information table and material information table establish a one-to-many relationship through supplier codes, while the logistics equipment table and inventory location table establish a many-to-many association through equipment numbers and storage location identifiers, ensuring accurate correlation between logistics path planning and equipment scheduling data.

3. Data collection and analysis methods

3.1. Data collection methods

This chapter focuses on the key technologies and implementation paths of data acquisition in the intelligent storage and logistics management system of thermal power plants. In the warehousing and logistics scenario, data collection is the basis of system construction and optimization. Through multi-modal sensor network, radio frequency identification (RFID) technology and IoT architecture, real-time perception and digital mapping of material status, equipment operation and logistics trajectory are realized. Specifically, the data collection method mainly covers the following technical paths and practical strategies.

Sensor technology is the core means of warehouse environment monitoring. In the storage scenario of thermal power plant, multiple types of sensors are deployed in the warehouse, transportation channel and key equipment nodes to collect physical parameters such as temperature, humidity, vibration, displacement and pressure. The temperature and humidity sensor network covers the storage space with a distributed architecture, monitors environmental changes through preset thresholds to ensure the stability of material storage conditions; displacement sensors and pressure sensors are integrated into stacker cranes, conveyor belts and other equipment to provide real-time feedback on mechanical displacement and load status, providing a basis for equipment operation status assessment. In addition, the vibration sensor is used to monitor the abnormal vibration frequency of the storage machinery, and the early warning of equipment failure can be realized by combining the frequency spectrum analysis algorithm [5]. All sensor data is transmitted to edge computing nodes via 4G/5G or LoRa wireless communication protocols. After preliminary filtering and noise reduction, structured data streams are generated.

3.2. Data analysis methods

In the development of intelligent warehouse and logistics management system of thermal power plant, data analysis method is the core link, and its scientificity and accuracy directly determine the reliability and efficiency of system decision. Data preprocessing is the basic step of data analysis, which mainly includes data cleaning, standardization and feature engineering. For the collected multi-source heterogeneous data, it is necessary to detect and correct the outliers by statistical methods, such as using box plot to identify outliers and using interpolation or mean to fill in the missing data. Subsequently, the data undergoes standardization to eliminate the impact of dimensional differences on the model. Common standardization methods include MinMax normalization and ZScore normalization. At the level of feature engineering, high-dimensional data can be reduced by using principal component analysis (PCA) or feature selection algorithms (such as chi-square test and information gain), which can not only reduce redundant information, but also improve the computational efficiency of subsequent analysis.

The selection of algorithms for data analysis should be based on specific application scenarios and data characteristics. Supervised learning methods are widely used in predictive analysis for structured data. For example, classification models such as random forests or support vector machines (SVM) can effectively identify abnormal inventory status, while multivariate linear regression and long short-term memory networks (LSTM) are suitable for time series prediction of fuel consumption [6]. In unsupervised learning, the K-means clustering algorithm dynamically categorizes warehouse materials based on turnover rates and value attributes, enabling differentiated inventory management strategies. Hierarchical clustering methods are employed for optimizing the topological structure of logistics routes. For unstructured data such as equipment operation logs or image recognition data, deep learning models (such as CNN) can extract key features to assist in intelligent processing of equipment fault warning or goods identification.

4. System development results and verification

4.1. System test results

In this study, a complete test environment is constructed to systematically verify the system function modules, performance indicators and integration stability. During the functional testing phase, 327 test cases were developed for core modules including warehouse management, logistics scheduling, data collection, and monitoring, achieving a coverage rate of 98.6%. The test of the warehousing management module shows that when the system handles random in and out operations of 10,000 pieces of materials, the average response time is stable at 0.42 seconds, and the data consistency check pass rate is 100%. In the simulation of 30 AGVs working together, the path planning time is controlled within 0.8 seconds, the transportation path optimization rate is 37% higher than the traditional algorithm, and the task conflict rate is less than 0.3%.The real-time performance test of the data acquisition module demonstrates that the RFID reader/writer maintains a data collection interval of ≤ 50ms with a 99.97% data transmission integrity rate, fully meeting the dynamic monitoring requirements for thermal power plant materials. The inventory monitoring module's threshold-based alert function achieves 100% accuracy in system alarms with a latency under 1 second when the safety stock range is properly configured.

For performance testing, JMeter is used to stress-test the system's concurrent access capacity. When simulating 100 concurrent users performing basic operations like inventory queries and order generation, the system achieved an average response time of 0.68 seconds with a TPS (transactions per second) of 120. When the number of concurrent users increased to 200, the response time rose to 1.2 seconds, while the TPS stabilized at 210 without any service degradation. Extreme stress tests demonstrated that the system maintained an error rate below 0.12% under continuous 250TPS pressure, with the database connection pool sustaining 92% availability even at peak load. During a 72-hour stability test, the core service remained uninterrupted, with memory leakage below 0.05% [7]. The logging system comprehensively recorded all operational logs and exception events.

4.2. Comparative method analysis

Through multi-dimensional comparative analysis with traditional warehousing and logistics management system, the development results of this system show significant technical advantages and practical application value. At the system architecture level, the traditional warehousing and logistics system usually adopts a decentralized management architecture and relies on manual operation to complete inventory records, material scheduling and process approval, which leads to low efficiency of information transmission and easy to produce data islands. In contrast, this system establishes an integrated architecture combining IoT and cloud computing. By deploying RFID tags, smart sensing terminals, and AGV systems, it enables real-time data collection and dynamic interaction across all warehouse elements. The system adopts distributed database and edge computing technology, which effectively solves the problem of response delay caused by centralized processing in traditional systems, and improves the data processing efficiency by more than 60% [8].

5. Conclusion

The system is developed based on the actual needs of thermal power plant storage and logistics management. By integrating IoT, artificial intelligence and automation control technology, an intelligent and modular storage and logistics management platform is built. The system has successfully realized the whole life cycle tracking of material information, automated scheduling of warehousing operations, intelligent optimization of logistics path and multi-dimensional data analysis, which has significantly improved the accuracy and logistics efficiency of thermal power plant warehousing management. At the technical level, the system establishes a real-time dynamic material status monitoring system through the deployment of RFID and sensor network, which effectively solves the problems of information lag and data island under the traditional management mode. Combined with deep learning algorithm, the system realizes the functions of material demand prediction, dynamic inventory balance and equipment fault warning, which provides data support for the scientific allocation of storage resources. In terms of function realization, the integrated application of automated warehousing equipment and AGV logistics system greatly reduces the manual intervention, improves the storage operation efficiency by more than 35%, and controls the material in and out error rate below 0.1%, effectively reducing the risk of manual operation.

Disclosure statement

The author declares no conflict of interest.

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