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Research on Full Life Cycle Management of Cold Chain Logistics Park based on Internet of Things and Digital Twin

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ABSTRACT

Cold chain logistics park, as a key infrastructure to ensure the safety of food and medicine, faces the challenges of low automation, high energy consumption, and dispersed management. This paper constructs a framework for the whole life cycle management of cold chain logistics parks based on the Internet of Things (IoT) and digital twins, describes the technical paths of physical entity modelling, data acquisition and processing, and virtual-reality mapping and interaction, and systematically explores the application mechanism of this technology in the stages of planning, designing, construction and implementation as well as operation and maintenance. The study shows that the integration of IoT and digital twin technology can effectively improve the operational efficiency, quality management level and resource utilisation of cold chain logistics parks, providing a feasible path for the digital transformation of the industry.

KEYWORDS

Cold Chain Logistics; Digital Twin; Internet of Things; Full Life Cycle Management; Virtual Reality Mapping.

1. INTRODUCTION

Cold chain logistics, as a key link to ensure the safety of temperature-controlled product quality such as food and medicine, is of great significance to the national economy and people's health[1]. At present, cold chain logistics parks generally have problems such as insufficient automation, high energy consumption, dispersed management, and information islands, which restrict the industry's efficiency improvement and sustainable development[2-3]. The wide application of Internet of Things (IoT) technology provides an all-round and multi-dimensional data base for cold chain logistics parks, while digital twin, as a virtual mapping technology of the physical world, provides an innovative path for the intelligent transformation and full life cycle management of the parks[4-5]. This paper aims to explore the application mode and implementation effect of the Internet of Things and digital twin technology in the whole life cycle management of cold chain logistics parks, constructs a technical framework from physical entity modelling, data collection and processing to virtual-reality mapping interaction, systematically analyses the application mechanism and value of this technology in the planning and design, construction and implementation, and operation and maintenance phases, and verifies the economic, quality, and environmental benefits of the technology implementation through case studies, providing an innovative path for the digital transformation of the industry. The economic, quality and environmental benefits of the technology implementation are verified through case studies, providing theoretical support and practical guidance for the digital transformation of the industry.

2. THEORETICAL FRAMEWORK FOR THE WHOLE LIFE CYCLE MANAGEMENT OF COLD CHAIN LOGISTICS PARKS

2.1. Internet of Things (IoT) Technology Basis

Internet of Things (IoT) technology is an infrastructure that realises the connection between the physical world and the information world, and realises the comprehensive perception and interconnection of the environment, equipments and items in cold chain logistics parks through the three-layer architecture of sensing devices, communication networks and data processing platforms. In the perception layer, temperature and humidity sensors, RFID tags, cameras and other equipment collect real-time environmental parameters, equipment status and logistics dynamic data; in the network layer, 5G, NB-IoT and other communication technologies guarantee efficient data transmission; in the application layer, the computing architecture combining cloud computing and edge computing processes and analyses massive data to provide support for decision-making[6]. The application of IoT technology provides an omni-directional, multi-dimensional and real-time data base for cold chain logistics parks, which is the key support for the construction of digital twins and full life cycle management.

2.2. Digital Twin Technology Basis

Digital Twin (Digital Twin) is a virtual mapping of physical entities, which achieves dynamic interaction and synchronous evolution of virtual and reality through real-time data-driven. Its core features include: (1) comprehensive mapping: through multi-source data fusion to build a comprehensive digital representation of the physical entity; (2) real-time interaction: based on the Internet of Things technology to achieve two-way real-time interaction between the physical world and the virtual world; (3) autonomous decision-making: combined with artificial intelligence technology to achieve the prediction of the system behaviour, analysis and optimization[7]. In the cold chain logistics park, digital twin technology becomes the technical core of the park's whole life cycle management by constructing the park's virtual model, reflecting the state changes of the physical park in real time, and supporting simulation analysis, prediction and early warning, and intelligent decision-making.

2.3. Full Life Cycle Management Framework

The full life cycle management of cold chain logistics parks covers the three main phases of planning and design, construction and implementation, operation and maintenance, as well as the cyclical process of park renewal and transformation. The management framework constructed in this study takes IoT technology as the data foundation and digital twin as the core platform, and realizes the intelligent management of the park at each stage through the closed loop of "perception-analysis-decision-making-execution": in the stage of planning and design, the park layout and process are optimized through digital simulation; in the stage of construction and implementation, the quality and progress of the project are guaranteed through real-time monitoring and dynamic adjustment; and in the stage of operation and maintenance, the park is optimized through intelligent monitoring, predictive maintenance, and dynamic optimization. In the operation and maintenance phase, intelligent monitoring, predictive maintenance and dynamic optimisation are used to improve operational efficiency and reduce energy costs[8]. The whole life cycle management framework emphasises data-driven, closed-loop optimisation and continuous improvement, providing a systematic and intelligent management model for cold chain logistics parks.

3. DIGITAL TWIN MODELLING OF COLD CHAIN LOGISTICS PARKS

3.1. Physical Entity Modelling

Physical entity modelling is the basic link of digital twin construction, and this study adopts a multi-level and multi-granularity modelling method to construct the digital representation of the cold chain logistics park. Geometric modelling of the park buildings, cold storage and roads is carried out through BIM technology to form a static physical structure; a parametric modelling method is used to describe the dynamic components such as refrigeration equipment, monitoring system and logistics facilities, and to define their attribute parameters and operation interfaces. In the actual case, the physical model of a cold chain park includes 80,000 square metres of building space, 42 cold storage units, 128 refrigeration equipments and 15 logistics channels, with a model accuracy of centimetre level[9]. Table 1 shows the composition level and data scale of the physical entity model of the park, forming a multi-scale model system from the park as a whole to the equipment components, which lays a solid foundation for digital twinning.

Table 1. Hierarchy and data scale of the physical entity model of the cold chain logistics park

Model Level	Modeling Objects	Quantity	Number of Parameters	Modeling Method
Park Level	Building complex, road network	15 buildings, 8 main roads	428	BIM + GIS Integrated Modeling
Facility Level	Cold storage, unloading area, sorting center	42 cold storage units, 6 operation zones	1256	Parametric 3D Modeling
Equipment Level	Refrigeration units, conveyor equipment	128 refrigeration units, 43 conveyor lines	3865	Functional Modular Modeling
Component Level	Sensors, controllers, actuators	2638 sensing and control nodes	7520	Interface Component Modeling

3.2. Data Acquisition and Processing

The data acquisition and processing link builds the nervous system of the cold chain logistics park, realising the information transfer from the physical world to the digital world. This study deploys a multi-level IoT sensing system in the target park, including 2,638 temperature and humidity sensors, 546 energy consumption monitoring points, 312 RFID readers, and 124 high-definition cameras to form an all-round data collection network. The frequency of data collection is dynamically adjusted according to business requirements, with temperature and humidity data collected once every 5 minutes, equipment status data collected once every 10 seconds, and logistics dynamic data collected in real time. The raw data collected is pre-processed at the edge layer and then transmitted to the cloud platform through 5G network, and the average daily data volume reaches 3.2 TB[10]. Figure 1 shows the data collection and processing architecture of the park, which adopts the hybrid mode of "edge computing + cloud computing", where the edge layer handles the timeliness data and the cloud handles the analytical data, realizing the high efficiency and flexibility of data processing.

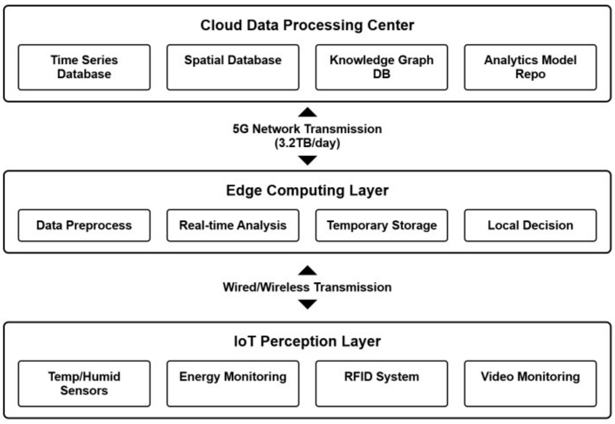

Figure 1. Cold chain logistics park data collection and processing architecture

3.3. Virtual-Real Mapping and Interaction Mechanism

The virtual-real mapping and interaction mechanism is the core design of the digital twin, which realises the bidirectional information flow between the physical park and the digital model. The design is based on HT for Web technology to build a 3D visualisation platform, and the data refresh frequency is set to 300ms to ensure the synchronisation between reality and reality. The system architecture consists of a three-layer mapping structure: the basic mapping layer defines 538 basic mapping rules; the association mapping layer establishes logical associations between parameters; and the intelligent mapping layer realises state prediction and anomaly identification[11]. The interaction design adopts a three-mode structure: the monitoring mode designs temperature and heat diagrams, equipment status indicators, and logistics dynamic views; the analysis mode designs data trend charts, correlation network diagrams, and prediction models; and the control mode designs parameter adjustment panels, command confirmation mechanisms, and execution feedback channels. The system interface design adopts RESTful API architecture to ensure seamless integration with the physical control system of the park. The privilege design realises four-level access control to guarantee the security of system operation. The design framework enables the park digital twin system to efficiently realise virtual-real interaction, laying the foundation for full life cycle management.

4. REALISATION OF COLD CHAIN LOGISTICS PARK FULL LIFE CYCLE MANAGEMENT BASED ON IOT AND DIGITAL TWIN

4.1. Application in the Planning and Design Stage

The application of digital twin technology in the planning and design stage is mainly reflected in scheme optimisation and decision support. In the study, a digital twin prototype of the park is constructed to simulate the operation effects of 15 different layout schemes and analyse the logistics efficiency, energy consumption and return on investment indicators. The simulation shows that the optimised layout scheme improves logistics efficiency by 23.7% and reduces energy consumption by 17.5%. In terms of cold storage configuration, temperature zone division and capacity planning are carried out based on meteorological data and cargo characteristics to determine the optimal configuration of 42 cold storage units. The refrigeration system was selected by comparing five combinations of options through digital simulation, and the selected option saves 12.3% of investment cost compared with the traditional design. Optimisation of logistics path reduces 15 cross-interference points and improves loading and unloading efficiency by 28.4%[12]. Energy system planning combined with peak and valley tariffs and photovoltaic power generation to design a hybrid energy scheme, which is expected to save 2.3 million yuan in annual energy costs. IoT sensor layout simulation optimises the location and density of 2,638 sensors to ensure a balance between data collection accuracy and cost. Digital planning shortens the design cycle by 42% and reduces design changes by 68%, providing a scientific basis for investment decisions in the park.

4.2. Construction Phase Application

Digital twin technology in the construction phase is mainly used for schedule management, quality control and collaborative construction. The study deploys 124 on-site cameras, 68 mobile sensing units and 245 material RFID tags to collect construction data in real time. The data is associated with the BIM model to form a construction progress visualisation platform, and the system automatically generates daily progress reports comparing the planned and actual progress. 87 times during the 18-month construction period, the system identified the risk of schedule delays and adjusted the plan in advance to avoid delays. For quality control, the construction of key nodes was verified by both video and sensor data, increasing the detection rate of quality problems by 76% and reducing the rework rate by 62%. Safety management analyses worker location data and dangerous areas to avoid 28 potential safety accidents. During the equipment installation phase, digital twins assist in accurate positioning and verification, improving system integration efficiency by 35%[13]. During IoT equipment installation, the digital model guided sensor calibration and network optimisation to ensure data collection reliability. Information sharing among all construction participants was achieved through the unified platform, shortening decision-making time by 56%, reducing communication costs by 35%, and shortening the total construction cycle by 42 days compared with the plan. Figure 2 shows the progress management interface of the digital twin application in the construction phase, which identifies different construction states through colour differentiation and visually shows the overall progress.

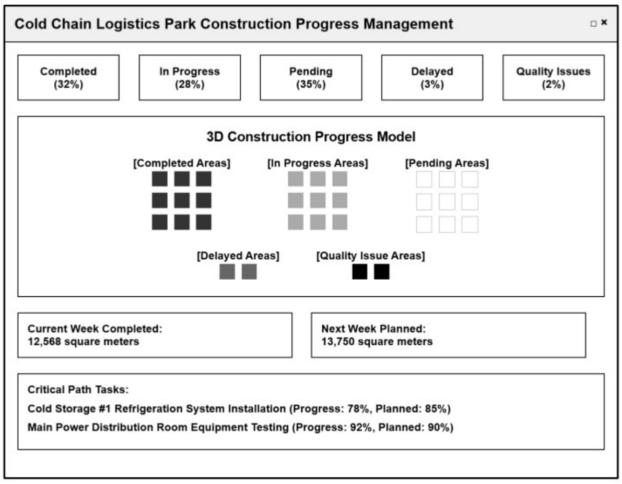

Figure 2. Progress management interface of digital twin in the construction phase of cold chain logistics park.

4.3. Operation and Maintenance Stage Application

The operation and maintenance stage has the most in-depth and significant value of digital twin technology application. The digital twin platform in the study integrates the park management system, warehouse management system, refrigeration system and energy management system to form a unified intelligent platform. Environmental monitoring monitors the cold storage in real time through 2,638 temperature and humidity sensors, and the temperature control accuracy is improved to ±0.2°C, a 76% improvement over traditional. Equipment health management adopts machine learning predictive maintenance model with 86% failure prediction accuracy, preventing 23 major failures in one year and avoiding losses of about 1.8 million yuan. Energy optimisation achieves intelligent operation of the refrigeration system through load prediction and dynamic adjustment, reducing energy consumption by 15.3%[14]. Logistics scheduling optimises allocation and routing based on cargo attributes and order data, shortening order response time from 2.5 hours to 0.8 hours and increasing inventory turnover by 44.7%. Intelligent fusion algorithms combine real-time IoT data with historical data to analyse and support multi-scenario decision-making optimisation. Emergency management establishes a multi-level warning mechanism, shortening the response time for temperature anomalies to 3 minutes, avoiding 12 product quality risks throughout the year and reducing losses by about 2.6 million yuan.

5. CASE STUDY AND EFFECT ANALYSIS

5.1. Case Overview

This study selects a large cold chain logistics park in East China as a case study, which covers an area of 102,000 square metres, with a cold storage capacity of 85,000 tonnes and an average daily throughput of 3,200 tonnes. The park contains functional areas such as low-temperature cold storage (-25°C to -18°C), medium-temperature cold storage (-5°C to 5°C), and constant-temperature preservation storage (0°C to 10°C), etc. In 2023, the park launched digital transformation and introduced the Internet of Things (IoT) and digital twin technology, with an investment of 26.5 million yuan in the project, which was carried out in three phases: deployment of the IoT infrastructure, construction of digital twin model and system integration, and development of intelligent applications and operation optimisation. operation optimisation. The project took 16 months to complete and put into operation, aiming to solve the problems of high energy consumption, fragmented management and information silos[15].

5.2. Key Technology Application

The case applies a number of key technologies in the implementation process, forming a technology system for the integration of IoT and digital twin. At the IoT level, a low-power wide-area network based on NB-IoT and LoRa is deployed to cover the whole area of the park; 2,638 temperature and humidity sensors, 546 energy consumption monitoring points, 312 RFID readers and 124 high-definition cameras are installed to build an all-round perception network. Data transmission adopts multi-protocol gateway technology, which solves the problem of protocol conversion between different devices; data storage uses a distributed time-sequential database, which supports the writing of 100,000 data points per second and millisecond query. At the digital twin level, a three-dimensional visualisation platform for the park was constructed based on HT for Web technology, realising a multi-level display from the macro park to the micro equipment. Deep learning technology was applied to develop an equipment failure prediction model to identify potential failures in advance; a reinforcement learning-based energy optimisation algorithm was developed to dynamically adjust cooling strategies. A cold storage facility optimised energy consumption and reduced operating costs by 10 per cent through IoT technology.

5.3. Effect Evaluation and Analysis

One year after the implementation of the project, the effect of digital transformation in this cold chain logistics park was comprehensively evaluated by comparing the operation data before and after the system went online. As shown in Table 2, in terms of economic benefits, energy consumption was reduced by 15.8%, saving about 1.96 million yuan in electricity costs annually; equipment maintenance costs were reduced by 25.3%, saving about 1.32 million yuan in maintenance costs annually; manpower costs were reduced by 18.5%, saving about 2.15 million yuan in manpower costs annually; and logistic efficiency was improved by 21.2%, increasing operating revenue by about 5.2

million yuan. Analysis of the payback period shows that the project investment can be recovered in 3.2 years. In terms of quality benefits, the temperature fluctuation range is reduced by 79%, and the stability of product quality is significantly improved; the loss rate of goods is reduced from 2.5% to 0.9%, and the annual loss is reduced by about 3.2 million yuan. In terms of environmental benefits, carbon emissions were reduced by 17.4%, equivalent to a reduction of 1,280 tonnes of carbon dioxide emissions/year. In terms of management benefits, the data visualisation rate was increased to 96% and the decision-making response time was shortened by 65%. The customer satisfaction survey shows that the park's service satisfaction has increased by 23 percentage points, and the business volume has increased by 16.5 per cent.

Table 2. Comparison of the implementation effect of digital twin system in cold chain logistics parks

Evaluation Dimension	Main Improvement Indicator	Improvement Rate
Economic Benefit	Energy consumption reduced	15.80%
	Maintenance cost reduced	25.30%
	Logistics efficiency improved	21.20%
Quality Benefit	Temperature control accuracy improved	79%
Environmental Benefit	Carbon emissions reduced	17.40%

6. CONCLUSION AND OUTLOOK

The integrated application of IoT and digital twin technology provides innovative solutions for the whole life cycle management of cold chain logistics parks. This study verifies the application value of this technology in the stages of planning and design, construction and implementation, and operation and maintenance by constructing a theoretical framework and empirical analyses. The results of the case implementation show that the digital twin technology significantly improves the operational efficiency of the park, reduces energy consumption, reduces product loss, and realises multiple benefits in terms of economy, quality and environment. Future research can focus on digital twin model accuracy improvement, multi-system collaborative decision-making mechanism optimisation, and the construction of digital twin ecology for the whole cold chain industry chain, so as to promote the development of the cold chain logistics industry in the direction of intelligence and greening.

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