

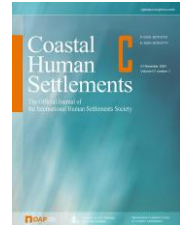


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Editorial

Design and Engineering Application of Hospital Energy Consumption Intelligent Supervision System Driven by Big Data

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ABSTRACT: To address the current issues of lagging, inefficient, and rudimentary approaches in energy consumption supervision, safety management, and equipment operation and maintenance within hospitals, an intelligent supervision system of hospital energy consumption based on big data and artificial intelligence has been designed and constructed. The system integrates IoT, AI algorithms, and digital twin technology to establish a closed-loop architecture of "perception-cognition-decision-execution," forming an intelligent operation and maintenance system centered on "digital employees." Engineering application at the Eye Hospital China Academy of Chinese Medical Sciences demonstrates that the system effectively achieves on-demand energy allocation, predictive equipment maintenance, and proactive prevention of safety hazards. This project propels hospital operations from informatization toward autonomous intelligent management, enhancing resource utilization efficiency and operational safety. It holds significant value for promotion and demonstration.

KEYWORDS: big data; artificial intelligence; hospital energy consumption; intelligent supervision; digital employees; intelligent operation and maintenance

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1. Introduction

Artificial Intelligence (AI) refers to the theoretical methods and technological systems developed to simulate and extend human intelligence. It encompasses core domains such as machine learning, natural language processing, and computer vision, involving interdisciplinary integration across mathematics, computer science, and neuroscience. Since its establishment at the 1956 Dartmouth Conference, the field has progressed through stages like symbolic reasoning and expert systems. Currently dominated by deep learning, it has formed a technological ecosystem featuring synergistic development of intelligent chips, algorithmic models, and big data. China formally introduced undergraduate AI programs in 2018, with 621 universities offering related majors by 2025. The disciplinary training system focuses on four modules: foundational theory, common technologies, supporting technologies, and applied technologies, encompassing core courses like machine learning and intelligent perception. As hospitals advance toward intelligent management, they still face prominent challenges such as excessive energy consumption, delayed security responses, and inefficient equipment maintenance, which hinder improvements in operational efficiency and service quality. With the maturation of technologies like big data, artificial intelligence, and the Internet of Things, building an integrated intelligent supervision system encompassing perception, cognition, decision-making, and execution has become a key pathway to enhance hospitals' comprehensive management capabilities. Conducting research on the design and engineering application of intelligent supervision systems centered on core hospital logistics and operational needs holds significant practical and promotional value.

2. System Design Philosophy

2.1 Autonomous Intelligence Framework

Hospitals, as densely populated, complex, and continuously operating environments, demand operational management characterized by high reliability, agility, and intelligence. To address challenges like imprecise energy consumption control, delayed safety responses, and equipment maintenance reliant on manual expertise, there is an urgent need to introduce an autonomous intelligent architecture with self-learning, self-sensing, and self-decision capabilities. This will drive the evolution of hospital operations from traditional informatization toward intelligence and ultimately to autonomous intelligence. The system design centers on an agent operating system as the core hub, coordinating the synchronized operation of all functional modules and endowing management processes with intelligent evolutionary capabilities. This framework moves beyond reliance on static rules and passive execution to build a dynamically evolving ecosystem of digital employees. Leveraging knowledge graphs, large models, and AI algorithms, it achieves multi-source data fusion and understanding alongside business strategy generation. The agent architecture enables hospitals to achieve real-time response, autonomous scheduling, and intelligent optimization

within complex and dynamic operational scenarios. It facilitates closed-loop control across the entire process—from equipment status sensing to safety risk alerts to energy consumption load balancing—propelling operational models from experience-driven to data-driven and ultimately to intelligent collaboration [1].

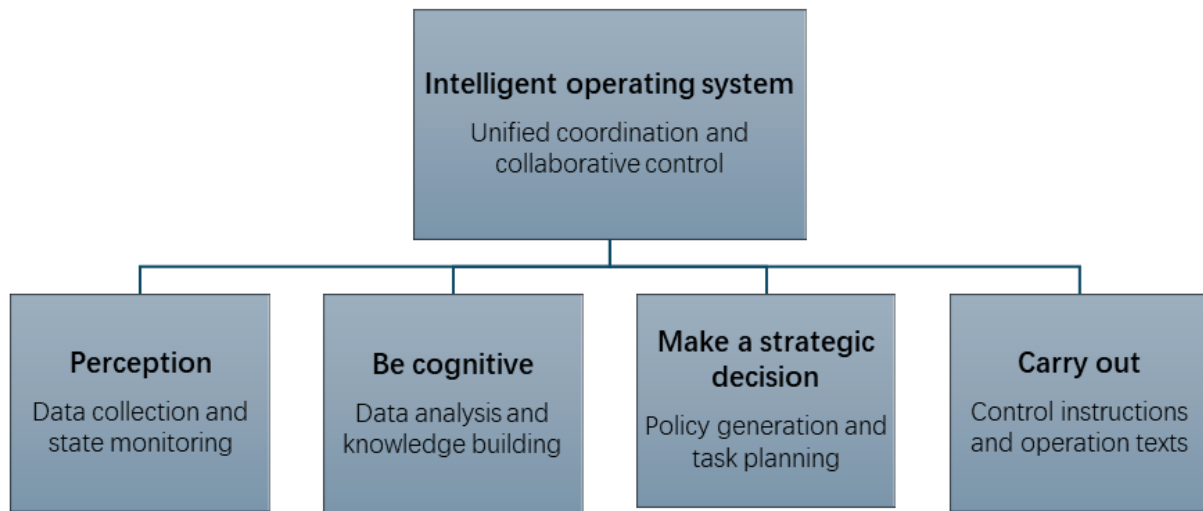


Figure 1. System Autonomous Intelligence Framework Model in the auxiliary computation phase, AI functions mainly as

2.2. Perception and Cognition Mechanism

The premise of intelligent management lies in comprehensive perception and deep understanding of hospital operations. The system achieves a high-fidelity digital mapping of physical spaces by constructing a multidimensional digital perception network that covers people, equipment, environment, and resources. The perception layer relies on energy metering devices, environmental and equipment status sensors, video surveillance systems, and edge computing nodes to build a unified IoT access platform that integrates multi-protocol, multi-type heterogeneous devices, and forms a sustainably evolving digital identity system. This enables a shift from static data collection to dynamic reconstruction of operational scenarios. In the data processing layer, the system introduces a multi-source heterogeneous data fusion mechanism to uniformly clean, time-align, and semantically annotate data from sensors, video streams, business system logs, and historical maintenance records, constructing a data platform that serves energy consumption, safety, and maintenance scenarios, and achieving collaborative management of structured and unstructured data.

The core of the cognitive mechanism lies in building a status and knowledge platform, transforming multi-source data into state parameters directly usable by the decision layer through feature engineering, event abstraction, and state modeling. These parameters characterize equipment operating conditions, energy load levels, and potential risk situations. Meanwhile, a symbolic knowledge graph is introduced to construct a hospital-specific domain knowledge system, structurally representing regulations, engineering standards, maintenance experiences, and expert rules, and enhancing the system's understanding of complex scenarios through semantic associations and relational reasoning. On this basis, combined with the semantic understanding and contextual modeling capabilities of large models, the knowledge graph is dynamically updated and reasoning-enhanced, enabling the system to maintain stable cognition and judgment even under data loss, uncertain states, or abnormal conditions, thereby providing reliable data and knowledge support for subsequent intelligent decision-making [2].

2.3 Decision-Execution Closed Loop

To enable the management system with real-time responsiveness and stable closed-loop execution capabilities, the platform has built an intelligent decision-making system and controllable execution mechanism for the entire business process. At the

decision-making level, a 'digital expert matrix' is deployed to form a virtual employee cluster composed of roles such as 'digital security officer,' 'digital operations officer,' and 'digital inspection officer.' Each digital employee possesses clear task domains, model capabilities, and execution boundaries, and collaboratively handles complex management issues under the unified coordination of the intelligent agent operating system. The decision-making reasoning process of digital employees comprehensively combines rule-based reasoning, reinforcement learning, and large model semantic reasoning: rule-based reasoning ensures deterministic execution in safety and compliance scenarios, reinforcement learning models optimize energy consumption and device operational parameters dynamically, and large models handle contextual understanding and strategy generation for complex events and multitask scenarios, thereby enhancing the predictability, correlation, and interpretability of decisions.

At the execution layer, a scenario-based intelligent closed-loop is established to map the action strategies generated by the decision layer onto specific systems and physical devices, achieving precise control and result feedback. The platform is equipped with a unified Intelligent Operations Center (IOC), which visualizes system operation status, task paths, and execution results based on BIM digital twin models, making the entire process of task generation, circulation, execution, and feedback transparent and traceable. In cases of anomalies and uncertainties, the system supports manual intervention and automatic strategy switching mechanisms; when sensor failures, communication delays, or equipment abnormalities occur, system operation safety and decision reliability are ensured through redundant sensing, historical state rollback, and manual confirmation. Work order systems, alarm response, and permission audit functions are embedded into the execution chain, enabling hardware-software integration and data feedback optimization, providing a data foundation for continuous platform learning and model iteration, and ultimately achieving a full-process closed loop and autonomous execution from state recognition to task completion[3].

3 Core Functionality Development

3.1 Intelligent Energy Regulation

As one of the main consumers of public energy, hospital buildings have a higher complexity in energy management than ordinary commercial facilities. This not only involves heating and cooling, electricity, water supply and drainage, gas, and medical-specific energy systems, but also requires dynamic adjustments based on ward schedules, medical procedures, and patient flow patterns. In traditional models, energy control is mostly set statically or manually inspected, lacking a real-time response mechanism to load changes. By building an AI-driven intelligent energy regulation system, relying on a comprehensive energy consumption sensing network, the system achieves real-time monitoring and dynamic aggregation of multi-source energy including water, electricity, gas, and heat. Based on LSTM time series prediction models and multivariable regression analysis methods, the system integrates multiple factors — historical load data, weather forecasts, patient volume, etc. — to predict and evaluate future peak energy demand and load characteristics. During model training, an outlier removal mechanism is introduced, and input variables are normalized to eliminate deviations caused by seasonal changes, holidays, or fluctuations in patient visits.

The system optimizes strategies using reinforcement learning (Deep Q-Learning), dynamically generating control strategies based on equipment parameters and operational efficiency indices. It precisely adjusts key devices such as air conditioning temperatures, lighting schedules, and pump speeds to achieve on-demand energy allocation and multi-source coordinated control. During scheduling, the platform dynamically aligns with electricity price curves, prioritizing off-peak operational strategies to improve energy efficiency. The sensing layer collects sub-metering data at multiple levels, including departments, zones, and individual devices, identifying abnormal energy usage patterns or potential leak points, triggering alerts, and creating handling work orders. Edge computing nodes are deployed at the execution end to enable localized load response and energy regulation, reducing latency and enhancing stability. For performance evaluation, the system uses year-on-year analysis and distribution fitting methods, combining six months of measured data before and after deployment to generate energy consumption comparison charts and single-device energy-saving analysis reports. Compared with traditional manual settings or timer-based control

methods, the platform, when applied in the target hospital, achieved an 11.2% reduction in air conditioning energy use, 7.6% energy savings in lighting, a 10.5% decrease in overall electricity consumption, and a 12.3% improvement in peak-valley electricity price utilization, demonstrating significant energy savings and stable operation [4].

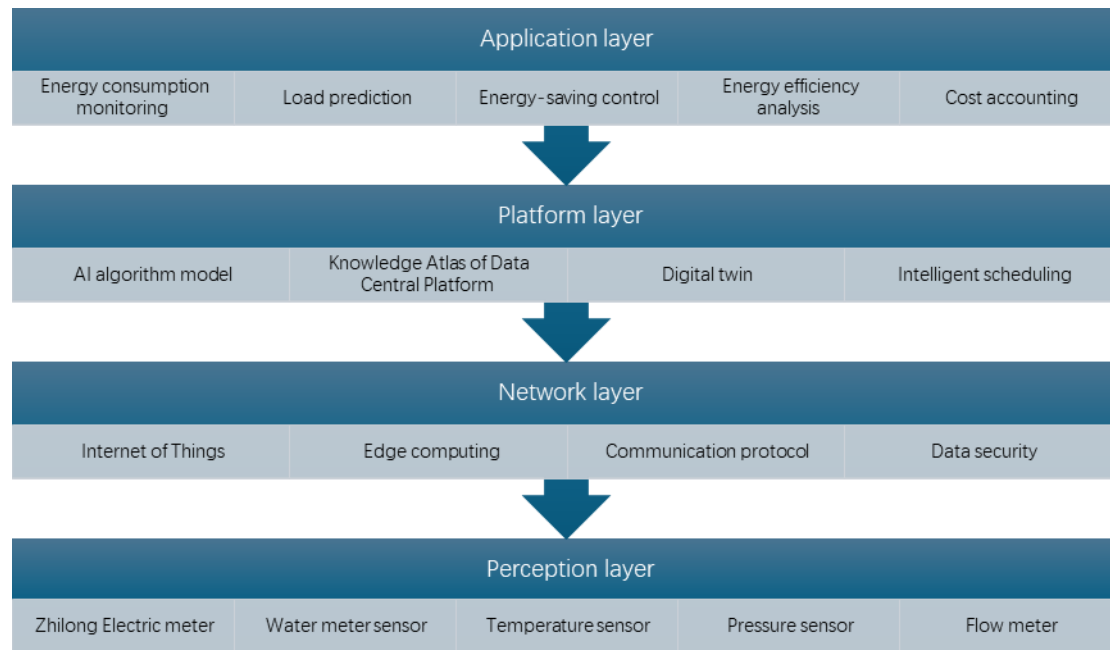


Figure 2. Hospital Energy Intelligent Control System Architecture.

3.2 Security and Compliance Management

Hospital operations involve numerous high-risk scenarios related to life safety, property safety, and legal compliance, including multiple sensitive areas such as hazardous chemical management, fire safety, access control, and radioactive material supervision. The system is built on a digital security officer framework and establishes an AI-driven proactive safety and compliance management mechanism. Relying on 24/7 multimodal sensing methods, the platform integrates video surveillance, environmental sensors, and business system data to dynamically identify, intelligently analyze, and close-loop handle safety hazards. The system uses the YOLOv7 image recognition model combined with a bidirectional LSTM event sequence analysis algorithm to identify key risk scenarios, such as blocked fire exits, unauthorized hot work, personnel gatherings, and failure to wear protective equipment. Meanwhile, smoke/gas sensors are used to detect air quality, flammable and explosive gas leaks, and changes in radioactive material concentrations, enhancing event detection accuracy. The platform has a built-in legal knowledge base covering national standards, industry norms, and local policies, using semantic matching algorithms to automatically compare legal provisions with on-site incidents. The system supports a 'one-click inspection' mode, automatically aggregating ledger records, monitoring data, and processing workflows, generating inspection checklists and accountability tracking paths to improve the completeness of audit materials. For complex scenarios, the system introduces a risk-level assessment model that automatically triggers response mechanisms and work order flow strategies based on risk ratings. The platform supports manual review processes and abnormal plan loading mechanisms, allowing manual intervention and workflow rollback in uncertain situations such as sensor failures or misidentifications, thereby enhancing system resilience[5].

3.3 Predictive Equipment Maintenance

The hospital's equipment system architecture is complex, covering multiple subsystems such as medical devices, power systems, HVAC, intelligent lighting, elevator facilities, and information terminals. The operating environment is variable and

the equipment is widely distributed. Traditional operation and maintenance rely on manual inspections and experiential judgment, leading to issues such as delayed fault detection, high maintenance costs, and low equipment lifespan utilization. The system, based on the concept of full lifecycle management, builds an intelligent predictive maintenance system that covers the entire process from equipment warehousing, operation, maintenance, spare parts management, to decommissioning. A cluster of intelligent agents, forming a digital maintenance team, is responsible for task planning and status assessment. Combined with the XGBoost prediction model and a CNN-based sensor image recognition model for feature extraction, the system identifies trends in critical equipment operation and subtle abnormal signals, enabling early fault warning and the generation of planned maintenance strategies. Equipment records support BIM integration, forming dual-dimensional associations of spatial location and operational information, visually presenting equipment operation status and fault trends. In terms of scheduling, the system allocates resources based on equipment health scores, usage frequency, and task priority, dispatching orders to responsible personnel in real time while tracking execution progress and maintenance quality. After system deployment, compared with traditional manual inspection methods, the platform increased equipment MTBF (mean time between failures) by approximately 15.2%, reduced unplanned downtime by 27.9%, shortened average maintenance response time by 36.5%, and improved spare parts inventory utilization by 22.4%. Additionally, the system, based on a lifecycle cost model, calculates each equipment's total operational expenditure and cost savings over its lifecycle and quantifies indirect benefits brought by predictive maintenance (such as uninterrupted medical cold chain and stable operating room function), providing decision-making support for refined hospital management.

4 Project Implementation

4.1 Platform Deployment Model

This project is deployed in the real operational environment of the Ophthalmology Hospital of the Chinese Academy of Chinese Medical Sciences. It integrates the hospital's existing building structures, equipment systems, and IT infrastructure, utilizing a hybrid architecture that combines localized deployment with edge collaboration. The core platform system is deployed in the hospital's data center, equipped with high-performance computing servers and private cloud management nodes to meet the computational resource needs for AI model execution, data integration, task scheduling, and policy orchestration. Edge computing nodes are deployed in the energy machine room, elevator control center, power distribution room, and key wards, enabling local data collection, preliminary processing, and policy execution to reduce network latency and bandwidth pressure. The deployment structure adopts a distributed master/slave coordination model. In the event of master node failure or network interruption, edge nodes can independently maintain local functionality with basic autonomy and task caching mechanisms, enhancing system robustness. The sensing layer uniformly connects to various IoT devices, including energy meters, water pressure sensors, motor vibration detectors, environmental monitoring modules, and video surveillance cameras, through MQTT, Modbus, and private protocol plugins, ensuring stable communication and data transmission across heterogeneous devices. The platform constructs a hospital BIM model based on digital twin technology, covering the main buildings, spatial structures, electro-mechanical equipment, and energy pathways, providing 3D scenario support and spatial positioning for system operations. The model-driven component supports a 'cold start' loading mechanism, enabling the system to perform initial policy configuration through rule reasoning and knowledge graphs even in the absence of historical data or upon first deployment. Subsequently, online learning and feedback optimization gradually enhance model adaptation. Considering significant differences between hospitals in building structures, equipment types, and data standards, the current system still relies on a certain degree of localized model fine-tuning and scenario reconfiguration, which limits the automation of model transfer. In the future, cross-hospital

scalability is planned to be improved through multi-source knowledge transfer and federated learning technologies. Once deployed, the system operates stably, seamlessly integrating logistics systems with the intelligent supervision platform without affecting existing medical workflows, ensuring 24/7 continuous operation and fault self-recovery capabilities.

4.2 Digital Employee Application

The digital employee matrix built on the platform serves as the core executing entity of the intelligent supervision system. It operates under the scheduling of the intelligent agent operating system and invokes virtual intelligent agents of different roles based on task attributes, including digital security officers, digital operations and maintenance officers, and digital inspection officers. Digital security personnel undertake around-the-clock risk scanning, compliance self-checks, and emergency response functions, integrating image recognition models (such as YOLOv7) with regulatory knowledge graphs to automatically review on-site images and identify violations. Digital operations personnel are responsible for energy regulation and equipment maintenance, using LSTM models to forecast air conditioning loads and electricity consumption trends, and scheduling air conditioning and pump systems to operate on demand, avoiding excessive startups or redundant energy use. Digital inspectors are deployed at edge nodes, combining path planning algorithms and SLAM mechanisms to perform unmanned automated inspection tasks. They conduct image comparisons and sensor data analysis for key areas, upload abnormal information in real time, and trigger processing tasks. Each role-based digital worker is embedded with a decision-making engine and an execution toolkit, equipped with capabilities such as state awareness, task planning, strategic reasoning, and instruction issuance. They support bidirectional interaction with work order systems, BIM platforms, energy consumption platforms, and alarm systems. The system supports concurrent collaboration among multiple digital workers. In complex scenarios such as fire alarms, sudden energy surges, or multiple equipment anomalies, the platform can automatically generate a joint task map and dynamically allocate role responsibilities, achieving cross-module coordination, information sharing, and joint handling, significantly improving response speed and task closure rates. To address situations like sensor failures, communication interruptions, or insufficient model confidence, digital workers introduce an uncertainty assessment mechanism during reasoning. When the decision confidence falls below a set threshold, it can automatically trigger a human confirmation channel or revert to a default safety strategy, ensuring the reliable execution of critical tasks.

4.3 Cost and Benefit Analysis

Platform construction investment comprises four components: hardware/software procurement, system development, and model training. Initial budget allocation leverages the Phase II Outdoor Power Supply Conversion Project at the Eye Hospital China Academy of Chinese Medical Sciences for partial implementation. Subsequent functionalities will be completed through a combination of government special funds and hospital self-financing. Post-deployment, operational data will undergo a six-month comparative analysis. Data collection utilizes system logs, automated uploads from energy meters, and statistics from the work order management system. Data is standardized by incorporating influencing factors such as weather and patient volume. Year-over-year analysis and multivariate regression methods will be employed to compare operational changes before and after system deployment. Research data indicates that after system deployment, overall energy consumption levels were effectively reduced without disrupting daily hospital operations. Electricity costs decreased by 8.3%, comprehensive energy consumption dropped by 10.5%, Water consumption decreased by 15.7%, primarily attributed to enhanced accuracy in predictive maintenance strategies and early warning models. Labor input was reduced by 423 workdays, reflecting the automation advantages of digital employees in routine inspections, hazard identification, and energy conservation control, thereby freeing significant human resources for higher-value roles. These data, sourced from the platform's automated recording system post-deployment and ana-

lyzed through standardized accounting models, demonstrate the project's comprehensive benefits in energy conservation, emission reduction, cost efficiency, and intelligent transformation. This validates the feasibility and scalability of the engineering solution.

5. Conclusions

The engineering practice of the intelligent supervision system in hospital operations demonstrates that the deep integration of big data and artificial intelligence not only elevates the intelligence of energy consumption control and equipment maintenance but also enhances the proactivity and compliance of safety management. The system achieves data-driven closed-loop perception/cognition and task execution, providing a technical pathway for constructing a highly reliable, low-cost, and efficient smart hospital operation system. The project outcomes are replicable, offering reference and technical support for the smart transformation of other medical institutions.

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