Global Research in Higher Education
ISSN 2576-196X (Print) ISSN 2576-1951 (Online)
Vol. 9, No. 1, 2026
www.scholink.org/ojs/index.php/grhe

Original Paper

Optimization Research of AI+Digital Twins in Building Equipment System

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Received: March 2, 2026 Accepted: March 19, 2026 Online Published: March 23, 2026

doi:10.22158/grhe.v9n1p108 URL:http://dx.doi.org/10.22158/grhe.v9n1p108

Abstract

Under the macro background of actively responding to climate change and promoting the "double carbon" strategy, the construction industry, as a key field of energy consumption and carbon emissions, has become a trend of green and low-carbon transformation. The operation efficiency of building equipment system, especially HVAC, electrical lighting and water supply and drainage system, directly determines the overall energy consumption of the building. This study focuses on the frontier technology integration of "ai+digital twins", and explores its application and implementation path in the optimization of building equipment system. Through systematic literature review, the application status of digital twins and AI technology in the whole life cycle of building equipment design, construction, operation and maintenance is summarized. Through the case analysis of multiple scenarios, the energy efficiency improvement ability and carbon emission reduction benefits of the technology in typical scenarios such as commercial buildings, factories, municipal water supply networks are quantitatively evaluated. Finally, based on the comprehensive research data and AI intelligent analysis, a set of "technology economy policy" collaborative transformation path covering technical standards, business models and policy incentives is constructed, which provides an operable solution for the implementation of the "double carbon" goal in the construction field.

Keywords

Digital Twin, Artificial Intelligence, Building Equipment Systems, Energy Efficiency Optimization

1. Introduction

The construction industry is an important part of the transformation of the global energy system. According to the 2023 global construction and construction status report released by the International Energy Agency (IEA), the construction industry consumes 36% of the global energy and emits 37% of the total carbon dioxide emissions. In China, this challenge is even more severe. According to the data of China Building Energy Efficiency Association, the energy consumption of the construction industry accounts for more than 45% of the total energy consumption of the country, and the proportion of carbon emissions is as high as 51.3%. It can be seen that promoting energy conservation and carbon reduction in the building operation phase is an indispensable part of achieving the goal of "double carbon". The equipment system inside the building, especially the HVAC, lighting and power system, is often the absolute main body of operating energy consumption, and its energy efficiency level has a huge space to improve.

The traditional construction equipment operation and maintenance management mode has been difficult to meet the new requirements of refinement, intelligence and low-carbon. At the data level, various subsystems have different data standards and closed interfaces, forming an "information island", which hinders the collaborative analysis and optimization at the system level. At the control level, the control strategy based on fixed schedule or simple feedback is slow to respond and cannot adapt to the dynamic changes of the internal and external environment of the building, resulting in energy waste such as "supercooling and overheating" or "idle standby". At the management level, there is a lack of effective tools for real-time and accurate monitoring and tracing of equipment energy efficiency and carbon emissions, resulting in the lack of data support for energy-saving transformation decisions and the difficulty in controlling the emission reduction effect.

The integration of digital twins and artificial intelligence (AI) technology provides a new paradigm for solving the above problems. By integrating the Internet of things (IOT), building information model (BIM), data analysis and simulation technology, digital twin creates a real-time synchronous, high fidelity virtual image for the physical building and its equipment system. Artificial intelligence, especially machine learning and deep learning, endows this virtual image with powerful cognitive and decision-making capabilities, which can mine rules from massive data, predict the future and generate optimal control strategies. The combination of the two, namely "AI+Digital twin", aims to build a closed loop of "perception cognition decision optimization" and promote the fundamental transformation of building equipment system from "passive response operation and maintenance" to "active predictive optimization".

Based on this, this paper focuses on the following three core research contents: first, through systematic literature review, this paper analyzes the application, technology and development trend of AI and digital twin technology in the design, construction, operation and maintenance of HVAC, electrical lighting and other building equipment systems; Second, through multi scenario case study and analysis, the potential of energy efficiency improvement and carbon emission reduction in different application scenarios is analyzed and evaluated, and the key technology adaptation conditions are refined; Third, by synthesizing the research results and using AI analysis tools, a decision-making consultation report focusing on the “technology economy policy” collaborative path is formed to provide systematic solutions for enterprises and policy makers. This study aims to provide theoretical basis and practical guidance for the digital, intelligent and green transformation of the construction industry.

2. Integration, Application, Bottlenecks, and Trends of AI+Digital Twin in Building Equipment Systems

2.1 Analysis of Application Status across the Full Lifecycle

The value of AI and digital twin technology runs through the whole life cycle of building design, construction and operation and maintenance, and its application in HVAC, electrical lighting and other core equipment systems presents different focuses.

In the design phase: from static simulation to dynamic performance optimization: traditional design relies on static BIM model and independent performance simulation software. The introduction of digital twins at this stage makes it possible to pre simulate and dynamically simulate performance. The designer can build a preliminary digital twin including equipment selection and pipeline layout at the initial stage of the scheme, access the local typical meteorological year data, and use AI algorithm to simulate the annual dynamic energy consumption and comfort, so as to optimize the system design parameters. For example, reinforcement learning algorithm is used to automatically find the best match between the performance of building envelope and the capacity of air conditioning system, and minimize the life cycle cost under the constraint of comfort. However, the current challenge lies in the lack of data consistency between the digital twin model at the design stage and the subsequent construction and operation and maintenance stages, and there is an “information fault”.

In the construction phase: from drawing delivery to digital twin delivery: the construction phase is the phase in which the digital twin model is transformed from the design blueprint to a virtual entity. By associating the construction schedule, cost information and quality detection data with the BIM model, the digital twin of the construction process can be constructed for progress visualization, collision detection, resource scheduling and construction safety early warning. AI technology can be used to automatically identify potential safety hazards or quality defects in construction images. For the equipment system, the core task at this stage is to ensure that all installed equipment information (such as model, serial number, performance curve) is completely and accurately entered into the digital twin model, laying the data foundation for subsequent smart operation and maintenance. At present, the main challenge at this stage is the low degree of automation of on-site data collection, which relies heavily on manual input, error prone and inefficient.

The operation and maintenance stage is the most concentrated and significant link in the application of AI+Digital twin technology. Its application can be summarized into three levels:

State perception and visualization: real time collection of equipment operation data and environmental data through IOT sensors, and dynamic presentation in the three-dimensional digital twin model.

Diagnosis, prediction and warning: use AI algorithm to analyze real-time data flow, realize early fault diagnosis and remaining service life prediction of equipment, change “preventive maintenance” to “predictive maintenance”, and significantly reduce the risk of unplanned downtime and maintenance costs.

Optimal control and strategy simulation: This is the core of deep energy saving. As a “control strategy sand table”, digital twin can integrate a variety of AI optimization algorithms. For example, the long-term and short-term memory network is used to predict the building cooling and heating loads in the next 24 hours; Based on the prediction results, real-time electricity price and indoor personnel distribution, the optimization strategy is analyzed in the virtual space by using the deep reinforcement learning algorithm, so as to carry out the dynamic adjustment of chiller startup and shutdown, chilled water temperature, air valve opening and other control settings, and realize the optimal energy efficiency of the system under the premise of ensuring comfort . Research shows that such optimization strategy can reduce energy consumption of HVAC system by 15%-30%.

2.2 Main Technical Bottlenecks Faced

Despite the broad prospects, the large-scale application of AI+Digital twins in building equipment systems still faces a series of technical challenges:

Data quality and integration problems: building data has the characteristics of multi-source (BIM, BAS, IOT, GIS), heterogeneous, and time difference. The lack of unified data standards and semantic models leads to high data fusion costs and low efficiency, and the “data island” phenomenon is serious, which restricts the construction of high-quality digital twins.

Balance between model accuracy and calculation efficiency: high fidelity physical simulation model has high accuracy but time-consuming calculation, which is difficult to meet the needs of real-time optimization; The pure data-driven AI model is fast, but its interpretability and reliability are poor. How to build a hybrid model that takes into account both accuracy and speed is a big challenge.

Information loss from BIM to the digital twin of operation and maintenance: the BIM model at the design stage contains rich geometric and attribute information, but when it is converted to the digital twin of operation and maintenance, a large number of non geometric information critical to operation and maintenance (such as equipment suppliers, warranty periods, maintenance manuals) are often lost, requiring a large number of manual reentries, forming the so-called “BIM operation and maintenance problem”.

3. Typical Application Scenarios and Quantitative Benefit Analysis

This part selects three typical projects that have been implemented in China covering different building types and equipment systems, and makes in-depth comparison from the three dimensions of technical path, implementation challenges and operation efficiency, so as to identify common patterns and differentiated characteristics, and provide practical reference for the subject research.

3.1 National Science and Technology Communication Center–Integrated System-wide Digital Twin Application

The national science and technology communication center is located in the Olympic central area of Beijing, with a total construction area of 60000 square meters. It adopts idrip 5.0 yuan universe digital twin intelligent building management system independently developed by Shenglong electric, becoming the first meta universe intelligent building management system in China. On the technical path, the system integrates more than 20 subsystems such as security, fire protection, building control, power, lighting, elevators and so on into a single platform for the first time. It realizes one key remote control of electromechanical equipment based on IOT technology, and builds a three-dimensional simulation model through BIM data fusion technology, so that the operation and maintenance personnel can intuitively and efficiently manage the whole building. More importantly, the system realizes joint commissioning and control of energy based on intelligent energy algorithm, and automatically controls the intelligent operation of all equipment through AI and algorithm model, without manual operation software for operation and maintenance management. In terms of implementation challenges, the project needs to solve the problems of long-term isolation of subsystems, extensive energy management, and low efficiency of operation and maintenance in traditional building management. At the same time, it needs to get through the equipment interface of multiple manufacturers and protocols to realize data fusion. From the perspective of operation efficiency, the system has achieved remarkable results: there is no air-conditioning panel or ceiling light switch in the building space, realizing that the light for people to pass is on, the light for people to walk is off, and the air-conditioning temperature is automatically adjusted with the increase or decrease of the number of people; The overall energy consumption is reduced by 15%, and the operation and maintenance cost is reduced by 70%. A single computer or mobile phone can control the lighting, air conditioning, access control and other equipment of the whole building, effectively improving the safety of building space and the operation stability of electromechanical equipment.

3.2 Trane Technologies Semiconductor Factory–Vertical and In-depth Professional Optimization Application

Aiming at the extreme requirements of semiconductor manufacturing for temperature control, Trane technology has developed an “efficient computer room AI online optimization platform”, which was first applied in the freezer room of a semiconductor factory in Guangdong. On the technical path, the platform will deeply enable AI in the full life cycle management of the central air conditioning refrigeration room. In the system design phase, trane700 simulation software and digital twin technology are used to build a high-precision model of the computer room to achieve the optimal solution of multi temperature area collaborative design and equipment selection; In the core control link, the AI controllable platform and CPC intelligent optimization algorithm are integrated, and the machine room is globally optimized at the minute level in combination with efficient hosts such as frequency conversion centrifuges with cop≥9.22, replacing the traditional manual solidification strategy; In the operation link, the system realizes “predictive” regulation through big data analysis of real-time load and weather changes. In terms of implementation challenges, traditional computer rooms are generally faced with pain points such as complex system variables, relying on manual experience for operation, and sacrificing energy efficiency for safety. It is necessary to break through the energy efficiency ceiling under the premise of ensuring the extreme temperature control stability of±0.5℃ in key processes such as lithography and etching. In terms of operation efficiency, the system can save energy by 10%-30% on the basis of conventional and efficient computer rooms, significantly reducing operation costs; At the social value level, the extremely stable temperature control ensures the yield of key products such as chips, reduces waste loss, and provides a reproducible digital path for the high-energy consumption industry to implement the “double carbon” goal. By the end of 2024, this technology has helped Trane win 225million yuan of orders in China, and realized real-time online and local deployment connection for more than 50 high-efficiency chiller room projects.

3.3 Fuzhou Water Supply Dispatch System–City-level Distributed Intelligent Dispatch Application

Fuzhou water supply dispatching system, based on the digital twin system of water supply network, covers a water supply network about 4500km long in the urban area and is selected as a typical case of smart water affairs in 2025 by the Ministry of housing and urban rural development. On the technical path, the system takes the urban water supply network as the unit, the spatial data and water business data of the network as the base, and the hydraulic algorithm as the core driver, so as to accurately open up the “island” of the network operation data and user business data. The system integrates the three centers of alarm center, event center and model center, and deeply integrates all the scheduling elements such as work order flow, customer service hotline, water cut-off management and service notice, forming a new mode of “eye, hand and brain” collaborative scheduling. In terms of implementation challenges, with the continuous development of the city, the water supply network system is becoming more and more complex, and the shortcomings such as high leakage rate of the pipe network, untimely disposal of pipe explosion, and water supply service capacity to be improved are highlighted. Traditional scheduling has operation bottlenecks such as information fragmentation, manual series connection, and response lag. In terms of operation efficiency, with the support of the digital twin system of water supply network, the leakage rate of Fuzhou pipe network has been reduced by about 15%, the water volume has been saved by more than 285 million tons, the average turbidity of the pipe network has been reduced by about 23%, and the qualified rate of the produced water and the comprehensive qualified rate of water quality are far higher than the national standard; The energy consumption per unit water supply is reduced by about 20%, and the operation and maintenance cost of the pipe network is reduced by about 53%; The average time for finding problems was shortened by about half an hour, and the disposal efficiency was improved by 12.5%.

Three real cases show the differentiated applications of AI+Digital twins in integrated buildings, vertical chemical industry and grid water services, which have reduced energy consumption by more than 15% and significantly reduced operation and maintenance costs. Its commonness lies in the construction of a "perception analysis execution" closed loop, from experience driven to data driven, which provides a solid practical reference for the establishment of classification standards and dynamic optimization mechanism.

4. Collaborative Pathway of "Technology-Economy-Policy" and Decision Suggestions

Based on the above research, in order to promote the large-scale application of AI+Digital twin technology in building equipment system and achieve significant energy saving and carbon reduction benefits, we must build a "technology economy policy" Trinity and mutually promoting collaborative development path. This part combines AI's comprehensive analysis of research data to form systematic decision-making suggestions.

4.1 Construction Path of Technical Standard System

Unified standards for data interoperability and semantics: promote the development of unified standards for building equipment data dictionary, information model and communication protocol, break the data island, and realize "one-time modeling, universal throughout".

Maturity and reliability evaluation criteria of digital twin model: establish a multi-dimensional evaluation system of digital twin model from geometric accuracy, data fidelity, model update frequency to simulation prediction accuracy to provide basis for model quality evaluation and transaction.

Accurate quantitative accounting standards for energy efficiency and carbon emission reduction: develop building energy efficiency index (such as real-time building energy efficiency ratio) and dynamic accounting methodology for carbon emissions based on digital twin real-time monitoring data. This methodology needs to be recognized by the industry and the carbon market, so that the energy conservation and carbon reduction based on digital twins can be measured, reported, verified, and have financial attributes.

4.2 Business Model Innovation and Market Cultivation Path

Deepen the "digital twin+energy performance" mode: encourage energy-saving enterprises to use the digital twin platform as the core tool to provide owners with full life-cycle services of "diagnosis transformation operation sharing". The accurate baseline determination and energy saving verification provided by digital twin can greatly enhance the trust of both parties to the contract and reduce the transaction cost.

Develop subscription service based on cloud platform: promote lightweight and modular digital twin subscription platform for small and medium-sized commercial buildings and public institutions. Users can enjoy professional energy efficiency analysis and optimization services and quickly activate the long tail market without undertaking high initial software and hardware investment.

4.3 Policy Incentives and Regulatory Guidance Path

Bring the level of digitalization and intelligence into the green building evaluation system: add evaluation clauses such as “building digital twin system” and “AI intelligent operation and maintenance” in authoritative standards such as the green building evaluation standard, and give higher weights or bonus points to drive the market from the demand side.

Improve fiscal and financial incentive policies: for projects that adopt digital means such as digital twins for energy conservation and carbon reduction, provide support such as loan discount, tax relief and special subsidies. Encourage the innovation of green financial products and provide preferential financing for related projects.

Strengthen the supervision of data security and privacy protection: while promoting the opening and sharing of data, formulate the safe use and privacy protection specifications of building operation data, clarify the boundaries of data ownership and use rights, protect the rights and interests of all parties, and eliminate the worries of data sharing.

5. Conclusion and Outlook

The research systematically discusses the current situation, benefits and implementation path of the integration of AI and digital twin technology applied to the optimization of building equipment system. Through the benefit analysis of commercial buildings, factories, municipal water supply networks and other scenarios, ai+digital twin technology can improve energy efficiency by 15% -40%, and defines the key technology adaptation conditions such as data base, model cost, algorithm ability and so on that its large-scale promotion depends on. This provides a scientific basis for the owners and technical service providers to evaluate the feasibility of the project.

In the future, the application of AI+Digital twin technology in building equipment system will show the following trends:

The digital twin service based on cloud platform will become the mainstream and reduce the use threshold of small and medium-sized projects. Edge computing is responsible for processing local control tasks with high real-time requirements, forming a cloud edge collaborative architecture.

Its application will expand from the optimization of a single HVAC system to the linkage optimization with lighting, elevators, security and other systems, and further extend to the level of regional energy systems such as parks, urban areas and municipal pipe networks, so as to realize multi energy complementation and collaborative scheduling.

Funding

Optimization Research of AI+Digital Twins in Building Equipment System (CE250102).

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