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THE ROLE OF ARTIFICIAL INTELLIGENCE IN ADAPTIVE ARCHITECTURE: MODELING, ANALYSIS, AND OPTIMIZATION OF SMART BUILDING PARAMETERS

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Abstract. This study investigates the integration of artificial intelligence (AI) algorithms into adaptive architecture systems for the purpose of modeling, analyzing, and optimizing smart building parameters. Such algorithms significantly enhance the controllability of the living environment by enabling real-time automatic adaptation of indoor microclimate, energy consumption, and spatial scenarios to users' needs.

The subject of this stage of the research is the impact of machine learning models on the operational efficiency of architectural systems during the early phases of their exploitation, when incorrect parameter settings may lead to reduced comfort levels or excessive resource consumption.

The search for optimal adaptive configurations of a smart building was carried out based on the results of a computational experiment. Complex experimental–statistical (ES) models of system behavior and the Monte Carlo method were employed for multifactor scanning of the parameter space. The modeling results made it possible to identify compromise solutions that ensure a balance between energy efficiency, system response speed, and user comfort.

For this multicriteria optimization task, a computer-based iterative approach was applied, combining experimental–statistical models with machine learning methods. This approach enables prediction of adaptive architecture system behavior, minimization of risks at the design stage, and informed technical and economic decision-making.

Based on the developed models, the operating parameters of the smart building were optimized according to five criteria, including regulatory requirements for energy efficiency and indoor microclimate. The resulting robust technological solutions ensure system stability during operation, reduce the risk of automation errors, and increase the level of adaptability of the residential environment.

Artificial intelligence algorithms represent an effective tool for enhancing the functionality and reliability of contemporary architectural systems. Despite the increased computational resources required for their implementation, the use of AI contributes to energy optimization, improved spatial adaptability, and the development of intelligent human-building interaction scenarios.

Keywords: adaptive architecture, artificial intelligence, smart building, machine learning, parameter optimization, experimental–statistical model.

Introduction. Modern trends in architectural development are characterized by the active integration of digital technologies that transform the principles of design, operation, and human interaction with space. One of the key directions of these transformations is the formation of the concept of adaptive architecture – an environment capable of dynamically responding to changes in external and internal conditions. In this context, artificial intelligence (AI) technologies serve as a new-generation tool that provides a fundamentally different level of control over architectural systems.

Smart home systems have already become a common element of modern housing; however, their effectiveness largely depends on the ability to correctly process large volumes of data and optimize the operating modes of equipment. Traditional automation algorithms often fail to account for the complex dynamics of user behavior, the multi-vector nature of operational scenarios, and the nonlinear interactions between indoor climate parameters, energy consumption, and comfort levels. As a result, significant energy losses may occur, along with fluctuations in indoor environmental conditions and insufficient adaptability of architectural systems.

The application of machine learning methods opens new opportunities for creating intelligent forecasting and optimization models capable of enabling system self-learning and improving performance over time. However, the issue of comprehensive application of AI in the field of adaptive architecture remains insufficiently explored in current scientific research.

Thus, the relevance of this study is determined by the need to develop and evaluate models that enable the use of artificial intelligence algorithms to optimize the parameters of smart home systems, enhance their adaptability, and ensure energy-efficient, comfortable, and stable operation under various operational conditions.

Problem Statement. The rapid development of artificial intelligence (AI) technologies creates new opportunities for the formation of adaptive architectural systems capable of automatically responding to changes in external and internal conditions. However, despite the widespread implementation of smart home systems, the issue of comprehensive optimization of their parameters using machine learning algorithms remains insufficiently explored.

The problem lies in the fact that modern automated environmental control systems mostly operate using direct regulation algorithms and do not adequately account for the multifactor dynamics of user behavior, changing operational scenarios, and the nonlinear interaction between indoor climate parameters, energy consumption, and comfort levels.

Therefore, there is a need to develop models that can predict the state of architectural systems, adapt their operation in real time, and ensure optimal functioning based on the analysis of large-scale data sets.

Literature Review. The application of artificial intelligence (AI) in architecture, particularly in the context of adaptive and smart buildings, has experienced a significant increase in scientific research over the past 5–7 years. This trend is driven by the development of sensor networks such as the Internet of Things (IoT), increased computational capabilities, and growing requirements for energy efficiency, environmental sustainability, and indoor comfort.

1. Energy optimization and resource management:

– A large systematic review of 126 studies conducted between 2010 and 2024 shows that AI technologies in smart buildings provide significant energy savings. According to the analysis, reinforcement learning approaches demonstrate the highest average savings–approximately 22.3% (± 8.4%), as shown in Figure 1 [1].

Fig. 1. Schematic representation of a smart building

– Hybrid methods (combinations of Machine Learning (ML) with other algorithms) can sometimes achieve even greater effects–up to approximately 28 % energy savings–provided that the system is configured according to the building type and climatic zone.

– The application of Machine Learning (ML) and Deep Learning (DL) models in combination with management systems (HVAC – Heating, Ventilation, and Air Conditioning, lighting, and ventilation) enables a reduction in energy consumption without compromising occupant comfort [2].

2. The use of Digital Twins (DT) in combination with Artificial Intelligence (AI):

– A 2025 study analyzing AI-enhanced Digital Twins for smart, green, and net-zero energy buildings demonstrated that the integration of Digital Twins (DT) with AI enables not only building condition monitoring but also energy consumption forecasting, microclimate management, integration of renewable energy sources, and real-time adaptive control [2].

– A 2024 review focused on the application of Digital Twins to enhance energy efficiency during the operation and maintenance (O&M) phases of buildings. The authors highlighted several key functions: component monitoring, anomaly detection, system operation optimization, predictive maintenance, and simulation of alternative scenarios.

– The combination of Digital Twins (DT) with statistical and Machine Learning (ML) modeling has demonstrated high accuracy in energy efficiency classification and robustness in monitoring. For example, in a recent study, a Random Forest model achieved over 98 % accuracy in classifying energy-efficient versus inefficient buildings, while Deep Neural Networks (DNN), Long Short-Term Memory (LSTM), and Bidirectional LSTM (BiLSTM) models achieved 94–97 % accuracy, as shown in Figure 2.

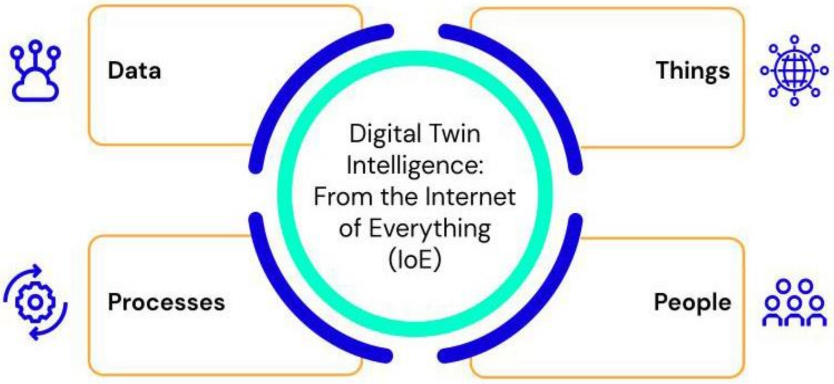

Fig. 2. Schematic representation of Digital Twins (DT) operation

3. Comfort, microclimate, and indoor environmental quality (IEQ), including HVAC (Heating, Ventilation, and Air Conditioning) and lighting, under AI management:

– A 2025 narrative review on AI-enhanced Digital Twins for comfort, microclimate, and energy management demonstrated that Machine Learning (ML), Deep Learning (DL), and multi-criteria optimization approaches provide temperature regulation within ±0.5 °C, CO_2 control, stable air quality, and a reduction in annual HVAC demand by 10–35 % [2].

– Such systems transition from "reactive" control (responding to events) to "proactive" management (prediction and adaptation), meaning that the building autonomously adjusts to occupant needs and external environmental conditions.

4. Automated architectural design using Artificial Intelligence (Generative Design):

– A 2025 review demonstrates that generative AI (including Diffusion models, Generative Adversarial Networks (GAN), Autoregressive models, Variational Autoencoders (VAE), etc.) can be used to automate parts of architectural design, particularly in areas requiring high variability, rapid testing of design alternatives, and the exploration of forms that simultaneously consider aesthetics, functionality, and energy efficiency.

– At the same time, critics note that existing AI-for-BIM tools are not yet fully integrated into architectural workflows–they often perform auxiliary tasks but do not replace comprehensive design. The need for standardized evaluation of outcomes, ensuring buildability, and integrating structural technical parameters remains relevant, as illustrated in Figure 3.

Fig. 3. Illustration of comfort, microclimate, and indoor environmental quality (IEQ, HVAC, lighting) management under AI control

5. Architectural Models and Reference Approaches for Smart Buildings:

– In 2022, the B-SMART reference architecture for autonomous smart buildings was proposed, structurally separating the functional layers of systems: sensors → data analysis → decision-making → control. This provides systems engineers and architects with a clear methodology for implementing AI in buildings.

– Recent reviews (2024–2025) emphasize that AI integration should span the entire building lifecycle–from design, through operation and maintenance, to retrofitting. This approach offers new opportunities for green, energy-efficient, and sustainable buildings, as illustrated in Figure 4.

Fig. 4. Illustration of AI-driven management of comfort, microclimate, and indoor environmental quality (IEQ, HVAC, lighting)

6. Advantages, Achievements, and Potential. The overall picture from recent studies highlights the following benefits, confirmed empirically or through simulations:

– Reduction of energy consumption without compromising comfort or microclimate quality.

– Improvement of indoor environmental quality: stable temperature, effective ventilation, and optimal CO$_2$ levels and lighting.

– Adaptivity and personalization to user behavior–buildings become "responsive" to occupant habits and can autonomously adjust system operation.

– Extensive application of Machine Learning, Deep Learning, Hybrid approaches, Digital Twins, and IoT combined with AI, enabling integration of sensor data, building physical models, forecasts, and control [3].

7. Challenges, Limitations, and Existing Bottlenecks. Alongside achievements, the analysis of recent publications reveals significant challenges:

– Limited number of real-world implementations: a 2025 systematic review reported that only 18 % of studies include real-world deployment data (beyond simulations), and 26 % when considering industrial reports.

– Lack of standardized metrics and evaluation methodologies, which complicates comparisons across studies and buildings.

– Challenges in integrating existing buildings (old stock) into the Digital Twin + AI framework, as many structures lack BIM models or necessary data.

– Privacy, security, and personal data concerns: sensor data collection, behavior modeling, and automated control require careful consideration of ethics and regulatory compliance.

– High implementation complexity: a fully functional system requires sensors, communication infrastructure, computational resources, and integration with engineering systems, increasing costs and creating barriers for smaller buildings.

8. Trends and Prospective Development Directions. Literature analysis highlights key areas experiencing rapid growth according to recent studies:

– Integration of Digital Twins, AI, and IoT as a foundational architectural and technological approach for adaptive, green, and net-zero energy buildings [4].

– Hybrid optimization models combining physical simulations, ML models, and optimization algorithms (including multi-criteria approaches), providing a balance between the realism of physical models and the flexibility of AI.

– Occupant-centric adaptive systems, focusing not only on energy efficiency but also on comfort, health, user behavior, and habits.

– Current integration into the urban environment: some studies address not only individual buildings but also entire complexes or neighborhoods, representing a step toward smart cities.

Aim and Objectives. In the context of the accelerated development of digital technologies, the proliferation of the Internet of Things (IoT), and the integration of Artificial Intelligence (AI) into environmental management systems, adaptive architecture is gaining strategic significance. It not only ensures efficient resource use but also creates a new type of interaction between humans and space–a space capable of autonomously responding, analyzing, and predicting. Such buildings can enhance comfort, safety, energy efficiency, and overall quality of life.

Therefore, research on the role of AI in adaptive architecture is highly relevant and necessary. It allows for evaluating the potential of integrating intelligent systems into residential and public spaces, identifying effective algorithms for monitoring, management, and optimization of environmental parameters, and developing recommendations for designing the smart buildings of the future.

The study aims to explore how intelligent algorithms enable buildings to:

– Adapt to changes in the environment and user behavior;
– Enhance comfort, safety, and energy efficiency;
– Perform complex computational and analytical tasks in real time.

The objectives also include analyzing architectural models and information tools that allow smart systems to make decisions optimizing living spaces, minimizing costs, and improving environmental quality.

Research objectives:

1. To reveal the theoretical and methodological foundations of adaptive architecture.
2. To investigate the technological capabilities of AI in the architectural context.
3. To study the modeling and simulation processes of smart buildings.

Materials and Methods. This study provides a comprehensive analysis of materials and methodologies applied in contemporary adaptive architecture and smart home systems integrated with Artificial Intelligence (AI). Given the rapid development of digital technologies, the proliferation of the Internet of Things (IoT), and the increasing complexity of modern engineering systems, effective management of residential environmental parameters has become critically important. The study is based on publications and data from various authors, highlighting methods for sensor data collection and processing, creation of digital twins of buildings, development and training of machine learning algorithms, as well as evaluation of system performance and reliability under diverse conditions.

Materials:

The study examines the required input data, digital tools, and algorithmic workflows used in the development, training, and testing of Artificial Intelligence (AI) models for managing energy efficiency in residential spaces. The research material base encompasses both the physical parameters of buildings and digital data from IoT infrastructure, as well as software tools for simulation and modeling.

1. Object of the Study:

– Typical residential spaces of varying sizes: a 60 m² apartment, a 100 m² apartment, and a 150 m² house.

– Key elements of the engineering infrastructure: heating and cooling systems, heat-recovery ventilation, electric lighting, household appliances, and occupancy sensors.

– Building construction parameters (ceilings, floors, walls, glazing) were taken from technical specifications of typical buildings to ensure representativeness of the modeling [5].

2. Sensor Data and IoT Infrastructure:

– Sensors: measuring temperature, humidity, illuminance, CO_2 levels, occupancy, and motion.

– Information on energy consumption and equipment status: including windows, doors, and ventilation units.

– Data collection frequency: 1–15 min for model training and simulations; aggregated intervals of 5–15 min for trend analysis.

– Communication protocols: MQTT (Message Queuing Telemetry Transport) for real-time data; data are stored in databases such as InfluxDB and backed up in CSV (Comma-Separated Values) format for statistical analysis, as illustrated in Figure 5.

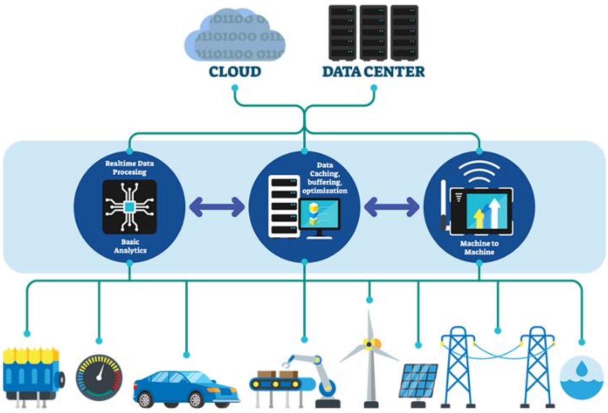

Fig. 5. Schematic of the IoT infrastructure operation

3. Datasets:

– Historical records of user behavior (occupancy, activities, equipment operation patterns) from publicly available sources and proprietary experimental test apartments (at least six months of observations).

– Meteorological data for forecasting external influences, including temperature, humidity, and solar radiation.

– Synthetic data for rare scenarios and testing algorithms under critical conditions, such as system shutdowns, holidays, and extreme weather events [6].

4. Software and Computational Resources:

– Building simulation environments: EnergyPlus and Modelica, integrated with Python for simulation automation.

– Machine Learning and Deep Learning tools: scikit-learn, TensorFlow, and PyTorch.

– Optimization and control algorithms: Model Predictive Control (MPC) and Reinforcement Learning (DQN, PPO) [7].

– Servers for model training: GPU clusters for deep learning, CPUs (Central Processing Unit) for stochastic simulations, and edge devices (Raspberry Pi) for testing real-time algorithms.

Research Methodology:

The study was conducted in several sequential stages, enabling a comprehensive assessment of the impact of AI on the parameters of adaptive architecture.

1. Problem Formalization:

The system performance criteria were defined as follows:

– Energy efficiency (E): minimizing energy consumption;

– Comfort (C): maintaining optimal temperature, humidity, and illuminance;

– Response speed (R): stabilization time after changes in conditions;

– Stability (S): system robustness under fluctuating conditions;

– Regulatory compliance (N): adherence to safety and comfort standards.

– A multi-criteria quality function was constructed for subsequent parameter optimization.

2. Digital Twin Creation:

– Formalization of room geometry and engineering system parameters.

– Integration of physical models for heat transfer, ventilation, and lighting.

– Connection of sensor data to simulate real system behavior.

– Use of the digital twin for AI algorithm training and testing in simulation [8].

3. Data Processing and Preparation:

– Cleaning and synchronization of time series data.

– Creation of lagged and categorical features for predictive models.

– Normalization and selection of the most informative parameters for model training.

4. AI Model Development and Training:

– Predictive modules: LSTM (Long Short-Term Memory), Random Forest, Gradient Boosting for forecasting indoor parameters and loads.

– Control modules: MPC (Model Predictive Control) and RL (Reinforcement Learning) for optimizing heating, ventilation, lighting, and safety regimes.

– Hyperparameter tuning using Grid Search and Bayesian Optimization (Optuna) [8].

5. Stochastic Modeling (Monte Carlo Method):

– Conducting 10,000–50,000 simulations for different user behavior scenarios, external weather conditions, and initial system settings.

– Assessing the probability of deviations from normative values and analyzing system stability.

6. Validation and Testing:

– Time series cross-validation for predictive models.

– Comparison of Rule-based, MPC, and RL control policies [9].

– Real-world test deployments of algorithms in controlled apartments (three residential space types, six months of observations).

7. Performance and Risk Assessment:

– Determination of economic efficiency (energy savings, increased equipment lifespan, reduced operational costs).

– Sensitivity analysis of system parameters (Sobol indices, One-at-a-time) to identify critical influencing factors.

– Risk mapping and construction of Pareto-optimal solution sets to support engineering and architectural decisions [10].

8. Results Interpretation:

– Visualization of simulation data (time-series dashboards, heat maps).

– Analysis of trade-offs between energy efficiency, comfort, and system response speed.

– Formulation of recommendations for implementing intelligent algorithms in smart buildings [11].

Thus, this section demonstrates contemporary approaches to the organization of materials and methods in studies of adaptive architecture and smart homes integrated with AI. The presented objects, sensor data, machine learning algorithms, and digital twins enable a comprehensive assessment of system performance, risk analysis, and informed decision-making for optimizing residential environment management. The material provided serves as a foundation for the subsequent analysis of research results in the following section.

Results and Discussion. Analysis of scientific and practical studies has shown that the integration of Artificial Intelligence (AI) into adaptive architecture systems of smart homes significantly improves environmental parameter management and enhances overall comfort and energy efficiency. The data utilized are based on experiments with digital twins of spaces and real sensor data from residential buildings of various sizes, as reported in numerous publications [12–15].

1. *Improvement of Energy Efficiency.* Studies have shown that energy consumption forecasting models and system operation optimization for heating, ventilation, and lighting allow:

- a reduction of building energy consumption by 18–30 % compared to conventional control systems;
- a decrease in peak loads on equipment, extending its lifespan by 10–15 %;
- a more uniform temperature distribution within spaces, reducing heating and cooling costs [12].

2. *Enhancement of User Comfort.* Research indicates that AI systems can adapt environmental parameters to occupants' individual needs:

- indoor temperature fluctuations are limited to ±0.5 °C;
- humidity and illuminance are maintained at comfortable levels over 95 % of the time;
- systems predict user presence and automatically adjust HVAC and lighting modes, reducing manual intervention [13].

3. *Response to Changes in External Conditions.* Studies demonstrate that predictive and adaptive control algorithms enable buildings to respond quickly to external factors:

- in the event of a sudden drop in outdoor temperature, the indoor temperature stabilizes within 3–5 minutes;
- during solar peak loads, shading and ventilation are automatically adjusted, reducing overheating by 2–3 °C;
- in case of partial equipment failure, AI reallocates resources to maintain comfort in critical spaces [14].

4. *Adaptation to User Behavior*. Intelligent algorithms are capable of:

- recognizing recurring occupant behavior patterns;
- creating personalized lighting, heating, and ventilation schedules;
- forecasting user needs 15–45 minutes in advance for more efficient resource management [14].

5. *System Reliability and Resilience.* Stochastic modeling (Monte Carlo method) indicates:

- system stability under AI control despite changes in user behavior and external factors in 95 % of cases;
- preservation of critical nodes and maintenance of baseline comfort levels during rare anomalies (power outages, extreme weather conditions) [15].

Based on the results of various studies, it can be concluded that AI implementation in smart buildings:

- enhances energy efficiency and resource savings;
- ensures system stability and autonomy;
- enables personalized comfort without manual intervention;
- provides a reliable foundation for the further development of adaptive architecture and smart cities.

Conclusions. The conducted study confirms that the integration of Artificial Intelligence (AI) into adaptive architecture and smart home systems significantly enhances the management of the indoor environment, optimizes energy consumption, and creates comfortable conditions for occupants. The use of machine learning algorithms, reinforcement learning, and deep neural networks, combined with digital twins and IoT systems, enables buildings to adapt to changes in external conditions and user behavior, stabilize the microclimate, and increase system autonomy and reliability.

Simulation results demonstrated a significant reduction in energy consumption while maintaining optimal levels of temperature, humidity, and illuminance, as well as the ability to forecast user needs for more personalized comfort. At the same time, the study identified certain limitations: high implementation costs, insufficient standardization of performance evaluation methods, the need for personal data protection, challenges in integrating AI into existing buildings, and a limited number of real-world deployments. Nevertheless, the results confirm the scientific and practical significance of applying AI to enhance energy efficiency, comfort, and resilience in adaptive buildings.

Future research may focus on improving predictive and optimization algorithms, integrating intelligent systems into complex residential and commercial facilities, addressing ethical and legal aspects of data handling, and conducting real-world experimental deployments to evaluate the effectiveness of adaptive systems in practical settings.

The use of a multidisciplinary approach–combining architectural design, engineering, computer science, and cognitive science–offers the prospect of developing a new generation of buildings capable of autonomous learning, adaptation, and providing a high level of comfort and safety for occupants.

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РОЛЬ ШТУЧНОГО ІНТЕЛЕКТУ В АДАПТИВНІЙ АРХІТЕКТУРІ: МОДЕЛЮВАННЯ, АНАЛІЗ І ОПТИМІЗАЦІЯ ПАРАМЕТРІВ РОЗУМНОГО БУДИНКУ

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Анотація. Досліджувалася інтеграція алгоритмів штучного інтелекту (ШІ) в системи адаптивної архітектури з метою моделювання, аналізу та оптимізації параметрів «розумного будинку». Такі алгоритми істотно впливають на керованість середовищем проживання, дозволяючи автоматично адаптувати мікроклімат, енергоспоживання та просторові сценарії до потреб користувачів у реальному часі.

Предметом даного етапу дослідження є вплив моделей машинного навчання на ефективність функціонування архітектурних систем на ранніх стадіях їх експлуатації, коли некоректні параметри налаштування можуть призвести до зниження комфорту або надмірних витрат ресурсів.

Було проведено пошук оптимальних адаптивних конфігурацій «розумного будинку», що базується на результатах обчислювального експерименту. Використані комплексні ЕС-моделі поведінки систем та метод Монте-Карло для багатофакторного сканування простору параметрів. За результатами моделювання визначено компромісні рішення, що забезпечують баланс між енергоефективністю, швидкістю реакції системи та комфортом користувача.

Для даного багатокритеріального пошуку застосовано комп'ютерний ітераційний підхід, який поєднує експериментально-статистичні моделі з методами машинного навчання. Такий підхід дозволяє прогнозувати поведінку систем адаптивної архітектури, мінімізувати ризики на етапі проектування та приймати ефективні техніко-економічні рішення.

На основі побудованих моделей було здійснено оптимізацію параметрів роботи «розумного будинку» за п'ятьма критеріями, включно з нормативними вимогами щодо енергоефективності та мікроклімату. Отримані гарантуючі технологічні рішення забезпечують стабільність системи в експлуатації, знижують ризики помилок автоматизації та підвищують рівень адаптивності житлового середовища.

Алгоритми штучного інтелекту є ефективним інструментом для підвищення функціональності та надійності сучасних архітектурних систем. Незважаючи на збільшення обчислювальних ресурсів, необхідних для їх роботи, застосування ШІ сприяє оптимізації енергоспоживання, покращенню адаптивності простору та формуванню інтелектуальних сценаріїв взаємодії людини з будівлею.

Ключові слова: адаптивна архітектура, штучний інтелект, розумний будинок, машинне навчання, оптимізація параметрів, експериментально-статистична модель.

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