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**Ruslan Minchenkov***
Postgraduate Student
Odesa State Academy of Civil Engineering and Architecture
65029, 4 Didrikhson Str., Odesa, Ukraine
https://orcid.org/0000-0003-1635-8317

# Architecture of a sustainable future: Smart building as a synthesis of technology and nature

**Abstract.** The purpose of this study was to provide a comprehensive analysis of smart building technologies and their integration into sustainable, energy-efficient, and intelligent urban environments. Smart buildings were considered as systems that combined automated solutions for heating, ventilation, air conditioning, lighting, shading, security, and engineering infrastructure management, coordinated through building management systems and implemented using Internet of Things technologies, sensors, and actuators. Such systems collected real-time data to enable predictive analytics, adaptive control, and energy optimisation. It was analysed machine learning methods, including supervised learning, unsupervised learning, reinforcement learning, fuzzy logic, and stochastic optimisation, for energy consumption forecasting, renewable energy management, intelligent control, and fault diagnostics. Occupant-centric control systems were investigated, as it accounted for human presence, preferences, and comfort, enabling dynamic adjustment of building operation modes and energy use. The integration of smart buildings with smart grids based on advanced building energy management systems was analysed, allowing participation in demand response programmes, voltage regulation, and distributed renewable energy management. The study also examined smart building-integrated photovoltaic and data-driven approaches for real-time forecasting of energy generation and consumption. Digital technologies, including building information modelling, digital twins, robotics, drones, edge computing, and cloud platforms, enhanced the efficiency of design, construction, monitoring, operation, and maintenance processes. Despite the evident advantages, challenges remained, including high implementation costs, cybersecurity risks, system interoperability issues, and the need for advanced data management infrastructure. The practical value of this study lies in applying the results in various stages of architectural practice, including the design of new buildings, the renovation and retrofitting of existing structures, and the ongoing management and optimisation of building operations

**Keywords:** machine learning; digital twins; occupant-centric control; energy management; smart grid; data-driven optimisation; sustainability

## INTRODUCTION

Smart buildings were central to sustainable and energy-efficient urban development. This study highlighted technologies that enhanced energy efficiency, occupant comfort, and environmental sustainability. It analysed international research and projects demonstrating how sensors, automated systems, and digital tools improved building performance, maintenance, and management. M. Casini (2022) reviewed virtual reality, augmented reality, and mixed reality for smart building operation and maintenance. Extended reality, integrated with digital twins, the Internet of Things (IoT), and artificial intelligence (AI), enhanced visualisation, energy control, predictive

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*Corresponding author

maintenance, and decision-making. While promising, practical guidance on device integration in the architecture, engineering, construction, and operation sector remained limited. S.F.A. Shah *et al.* (2022) emphasised that machine learning and IoT enabled real-time monitoring, automation, and data-driven energy optimisation. Integration of AI and IoT improved occupant comfort, safety, and operational management, although security challenges must be addressed.

H. Teixeira *et al.* (2025) reviewed solar-control smart glazing technologies, including electrochromic, thermochromic, photochromic, gasochromic, suspended particle, and liquid crystal glazing. Electrochromic and thermochromic glazing were the most studied and effective for energy savings and thermal and visual comfort. The review identified gaps in holistic performance assessment across climates and barriers like cost, installation complexity, and market adoption. A. Behzadi *et al.* (2026) investigated model predictive control (MPC) for optimising thermal systems. In low-temperature heating and high-temperature cooling systems integrated with ground-source heat pumps and borehole thermal energy storage, MPC reduced operational costs by 13%, increased long-term savings by 20%, and shortened payback periods compared to rule-based control, while maintaining comfort and lowering $CO_2$ emissions. MPC demonstrated robustness under forecast uncertainty and scalability for next-generation smart buildings. S.S. Kumaresan & P.R. Jeyaraj (2025) proposed transferable reward-shaping deep reinforcement learning for energy scheduling in IoT-connected buildings. Using an aggregator for real-time appliance data, optimal scheduled balance energy savings, peak load reduction, and user comfort. Simulations and tests achieved up to 19.2% energy savings, 6.45% peak load reduction, and a satisfaction index of 0.93, showing adaptive, data-driven energy management enhanced grid stability and operational efficiency.

Researcher L. Qiu (2025) developed a reinforcement learning-based adaptive energy management system for heating, ventilation, and air conditioning (HVAC) systems, lighting. Testing in 89 buildings showed 27% energy reduction, 32% lower peak loads, comfort maintained for 96% of occupied hours, and 24% lower energy costs. The system adapted quickly to occupant behaviour and weather conditions, demonstrating effectiveness for sustainable energy management. S. Padmanaban *et al.* (2025) described smart buildings as IoT networks enabling control of lighting, ventilation, air quality monitoring, energy and water tracking, and consumption pattern analysis. These systems improved energy efficiency, comfort, security, and productivity, positioning IoT as a key building management and automation solution. M. Almadani *et al.* (2025) presented a conformalised light gradient boosting machine combining quantile regression with conformal prediction for short-term energy demand forecasting. Tested on commercial buildings from the LEAD-1.0 dataset, the model provided point and probabilistic forecasts with 90% coverage, adapted to variable consumption patterns, and reduced forecasting errors compared to baseline methods. This approach enhanced operational efficiency, anomaly detection, and decision-making in smart building digital twins, while remaining computationally efficient and scalable.

M. Feng & H. Wu (2025) proposed a smart building BIM (Building Information Modelling) co-design model integrating IoT and blockchain. Using a hyperledger fabric federated blockchain with a revolving door compression algorithm and SDT updates, the method improved data security, reduced redundancy, and enhanced collaboration efficiency. Experiments showed faster response and higher throughput, though practical validation was still needed. By integrating digital modelling tools with real-time data, stakeholders were able to simulate demolition scenarios, optimise resource management, reduce environmental impact, and minimise technical and financial risks. This approach enhanced transparency and decision-making reliability throughout the project lifecycle. The aim of this study was to provide a comprehensive analysis of modern technologies and approaches applied in smart buildings, focusing on energy efficiency, occupant comfort, digitalisation of building management, and the integration of advanced technologies such as IoT, AI, BIM, digital twins, and predictive analytics.

## MATERIALS AND METHODS

The research was conducted using a comprehensive analytical approach that combined theoretical analysis, comparative study of implemented projects, review of international reports, and systematisation of digital building management technologies. At the first stage, a review of scientific publications, international standards, and certification systems was carried out, including BREEAM (n.d.), German Sustainable Building Council (n.d.), U.S. Green Building Council (n.d.), European LEVEL(s), and SRI (European Commission, 2010). This stage made it possible to formulate evaluation criteria for energy efficiency, digital readiness, and environmental sustainability of buildings. At the second stage, the structure and operating principles of smart building systems were analysed. This included sensor networks (temperature, humidity, $CO_2$, occupancy sensors), actuators, HVAC systems, adaptive lighting, automated shading, and security systems. Data on occupancy levels, energy consumption, and indoor environmental parameters were considered key variables for optimisation. Building Management Systems (BMS) were examined as centralised platforms that provided monitoring, automation, and predictive maintenance. Data processing was examined from the perspective of applying Big Data analytics, Machine Learning (ML), and Reinforcement Learning for energy forecasting, fault detection, and adaptive control. BIM and digital twins were analysed as integrative platforms that combined a static building model with dynamic sensor data. Deep Learning (DL) methods were considered for video stream analysis and occupant counting in order to adjust system performance in real time. Particular attention was paid to Demand-Side Management (DSM) and predictive control strategies for load balancing and peak energy reduction. The research also considered the integration of renewable energy systems (photovoltaic modules and green roofs) and smart materials to improve overall building performance. For example, the study analysed data from the Beijing National Aquatics Centre (the "Water Cube", Beijing). In addition, a report by the ACEEE (American Council for an Energy-Efficient Economy) was examined (King & Perry, 2017). Thus, the research methodology was based on the integration of theoretical analysis, international experience review, and systematisation of technological solutions, allowing for a comprehensive assessment of the potential of smart building technologies in shaping energy-efficient and sustainable urban environments.

## RESULTS AND DISCUSSION

The concept of a smart building had become central to the creation of sustainable, energy-efficient, and intelligent architectural environments. Unlike traditional buildings, smart buildings integrated automated systems that regulated heating, ventilation, air conditioning, lighting, and shading based on real-time data from sensors. This ensured optimal indoor conditions, reduced energy consumption, and improved comfort. Their operation was coordinated through BMS, which allowed centralised control, monitoring, and analysis of all building subsystems, improving efficiency and enabling predictive maintenance. The development of smart buildings had been driven by rapid advances in IoT technologies, which allowed the continuous collection of data on building performance, occupancy, and environmental conditions. Cloud computing and machine learning algorithms enabled the processing of large data sets, supporting informed decision-making and real-time system optimisation. The introduction of edge computing further enhanced responsiveness by allowing local processing of sensor data with reduced delays.

A smart building aimed to anticipate user needs and operate autonomously, adjusting temperature, lighting, shading, energy and water use without human intervention. In this context, smart buildings contributed to improving quality of life and reducing environmental impact, while increasing cost efficiency. Smart buildings were evaluated according to a number of frameworks that emphasised energy efficiency, automation, sustainability, and intelligent system integration. International systems such as BREEAM (n.d.), German Sustainable Building Council (n.d.), and the U.S. Green Building Council (n.d.), European LEVEL(s) framework (a European framework for assessing the sustainability of buildings) provided guidelines for designing and assessing sustainable and environmentally responsible buildings. Regarding technological readiness, initiatives such as the European SRI assessed a building's digital capability, sustainability, and operational reliability, providing a standardised framework for evaluating smart building performance (European Commission, 2010).

Data analytics was crucial in smart building evaluation. By analysing data from sensors and meters, buildings can detect anomalies, predict failures, optimise energy use, and improve operational strategies. Digital twin technologies – virtual models of physical buildings updated in real time – were becoming an important tool in advanced smart building management. However, their implementation required significant investment in sensors and data infrastructure, as well as strong cybersecurity measures. Overall, smart buildings represented a shift towards adaptive, data-driven, and environmentally responsible architecture. While many evaluation frameworks exist, a key challenge remained the integration of environmental, technological, and operational indicators into a unified assessment system. Understanding what made an intelligent building fundamentally different from a conventional one was crucial, as this influenced architectural and engineering decisions. In many commercial interpretations, a smart building was reduced to remotely operated systems controlled by users, offering automation but no independent decision-making or adaptation. A more advanced perspective defines such a building as a system capable of monitoring indoor and outdoor conditions, identifying user behaviour patterns, learning from accumulated data, and initiating responses without direct human input. In this case, the building acted as an autonomous participant in the interaction with its occupants, optimising its functioning based on real needs.

Research and experimental projects developed by leading universities – such as the Smart Living Lab at EPFL and the University of Fribourg, the SM4All smart home interoperability project involving Sapienza University of Rome, and university-based smart building testbeds for real-time IoT data collection and control – demonstrated that truly intelligent environments provided a broad spectrum of advantages, including improved user comfort, reduced resource consumption, time savings, higher safety standards, integration of expert knowledge, support of healthy indoor conditions, and assistance for elderly or disabled residents through automated monitoring and alerts. These capabilities rely on three elements working together: hardware that gathered information about the environment and building operation; software that analysed data, identified patterns, and made decisions; and communication networks that connected all components into a unified system (European Commission, 2010; Smart Living Lab, n.d.). To determine how advanced a building was, several evaluation models calculated the share of parameters and processes that the system can monitor and regulate independently. This allowed specialists to distinguish between simple automation, where the user remained the primary decision-maker, and full intelligence, where the building detected changes and responded proactively. A higher score indicated greater autonomy, adaptability, and technological sophistication (Apanaviciene *et al.*, 2020). Progress in smart building technologies had enabled the creation of integrated systems that combined information technologies with building automation to improve energy performance and reduced operational costs. Modern solutions relied on a network of sensors, actuators, communication hardware, management software, and intelligent control devices that operated together within a unified digital environment. Control units and sensing devices were distributed throughout the building and connected to a central platform capable of exchanging data in real time. Each subsystem had its own communication channels, but all operated on a shared network infrastructure, which functioned as the technological backbone of the building (Fig. 1).

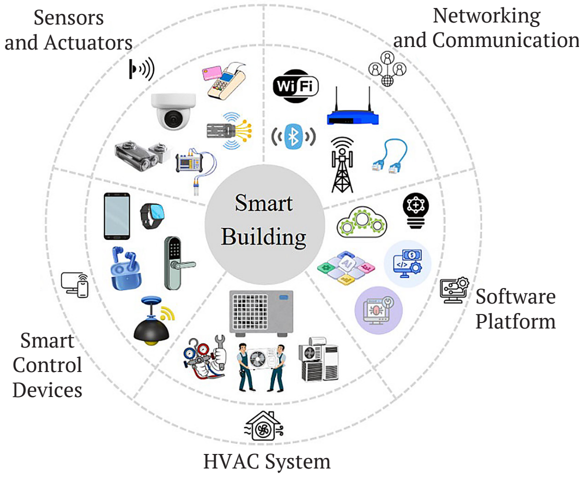

**Figure 1.** Integrated smart building framework

**Source:** based on B. Qolomany *et al*. (2019)

Among all technical installations, HVAC systems remained the most complex, as it ensured thermal comfort, air circulation, and indoor air quality, while also accounting for a major share of total energy use. Their correct operation directly influenced environmental performance and user safety. Smart buildings continuously supervised these systems and adjusted their operation automatically. The main goal was to manage lighting, security, ventilation, climate control, and other services from a single digital interface supported by computer-based decision mechanisms. The Honeywell Total Connect Remote Services platform integrated home automation functions with professional security monitoring. Through a mobile application or a dedicated control console, residents can manage lighting, shading devices, cameras, alarms, and other connected systems, while receiving instant notifications about events in the home. The solution also offered remote video access and location tracking for vehicles and assets. The system was compatible with Z-Wave equipment and must be installed by a certified Honeywell provider. It does not support Wi-Fi based smart thermostats but can operate with Honeywell cameras, sensors, and selected external products such as Lutron lighting controls and Yale electronic locks. A comparative overview of smart controllers used in modern buildings was presented in Table 1.

**Table 1.** Comparative analysis of smart home devices

| Device | Communication technology | Supported platforms | Main advantages | Main limitations |
|---|---|---|---|---|
| WeMo | Wi-Fi | Android, iOS, Windows, Phone | Low-cost ecosystem; scalable via SmartThings and IFTTT; easy entry into smart automation | No dimming support; lacks colour lighting; occasional signal latency |
| Nest Thermostat | Wi-Fi, ZigBee, Thread | iOS, Android, Windows, macOS | Learns user behavioural patterns; adapts heating/cooling schedules automatically; strong energy-saving potential | Higher cost than many competitors; may lack manual fine-tuning preferred by some users |
| Lockitron | Bluetooth | iOS, Android | Keyless and proximity-based unlocking; silent operation; user-friendly installation | Wi-Fi bridge purchase required for remote access; limited device interoperability |
| SmartThings Hub | Wi-Fi, ZigBee, Z-Wave, Bluetooth | Android, iOS, Windows Phone | Multiprotocol support; can integrate multiple third-party devices; quiet and reliable operation | Compatibility issues may occur with non-native devices; configuration complexity for some users |
| Philips Hue | Wi-Fi | iOS, Android | Wide integration support; large community; deep customisation via scenes, scheduling, and smart automation | Higher product cost; some features harder to configure for beginners |
| BluFit Bottle | Bluetooth | iOS, Android | Easy setup; helps users monitor hydration; attractive design | Premium price compared to conventional solutions |

*Table 1. Continued*

| Device | Communication technology | Supported platforms | Main advantages | Main limitations |
|---|---|---|---|---|
| Canary Security System | Wi-Fi | iOS, Android | Simple installation; central smart security functions in a single unit | Expensive for its feature set; limited mainly to internal monitoring |
| Amazon Echo | Wi-Fi, Bluetooth | FireOS, Android, iOS | Excellent voice recognition; supports integrations across major ecosystems; universal compatibility | Intruder detection limited to indoor audio triggers; depends on constant cloud connectivity |
| Honeywell Smart Thermostat | Wi-Fi, Z-Wave | iOS, Android | Reliable installation; balanced functionality; integrates well with multi-device smart homes | Higher cost than similar competing thermostats |

**Source:** based on B. Qolomany *et al.* (2019), D.D. Eneyew *et al.* (2022)

In the process of seeking solutions to complex problems, building technologists often turn to nature for inspiration. Biomimetics lain at the intersection of biology, biophysics, and materials science, requiring comprehensive knowledge in these fields. In the context of smart buildings, biomimetic principles inspired the design of adaptive and energy-efficient systems. For example, building façades can emulate the self-shading patterns of leaves to optimise natural lighting, while ventilation systems can mimic the airflow strategies observed in termite mounds to enhance indoor air circulation. Openness to new ideas and active interdisciplinary dialogue facilitated the translation of biological strategies into architectural solutions, enabling the creation of responsive, sustainable, and resilient building environments. Although the evolutionary processes in nature span millions of years, their principles can inform rapid technological innovation in smart building design. The differences in time scales, the design constraints and objectives remained similar: ensuring functionality, optimisation, and efficient scalability (Degha *et al.*, 2019). Modern evolutionary step in construction, emerging in the late 20th century (approximately 1980s-1990s) and continuing into the 21st century, involved the concept of smart materials. These materials were divided into passive materials, which sense environmental functioned as sensors, and active materials, which also acted as actuators in response to such stimuli. Intelligent materials are capable of autonomously adapting to changing environmental conditions. Examples of smart building components included windows and blinds that regulated light and temperature through technologies such as shape-memory alloys or suspended particle devices (Fig. 2).

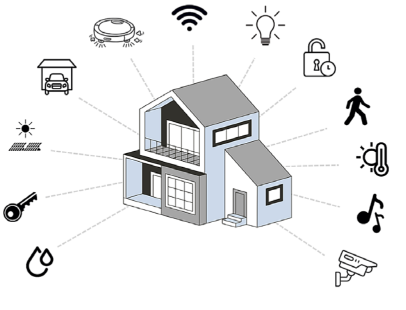

**Figure 2.** The concept of smart home and its advantages
**Source:** based on S. Vattano (2014)

Roofs can incorporate renewable energy sources, such as green roofs and photovoltaic modules, producing electricity for the building. Anti-microbial ceilings feature coatings that inhibited bacterial growth, preventing odors and stains (Dong *et al.*, 2019). Using DSM approaches in home energy management systems (HEMS), electricity consumption can be effectively regulated. To reduce user stress, the synchronisation of different household appliances was proposed, enabling a more efficient response to unexpected events. Users can reorganise their schedules to pause one appliance and reallocate the freed time slot to other devices of their choice using dynamic programming. This allowed for shorter waiting times for higher-priority devices (El-Afifi *et al.*, 2024). Urban renewal drove economic development and job creation but also produced significant amounts of construction and demolition waste (CDW), which can negatively affect the environment, public health, and urban infrastructure. Efficient management of construction and demolition waste was often hindered by insufficient data collection, limited recycling practices, and lack of integrated technologies. It was presented a smart demolition and waste management framework that combined image-based three-dimensional (3D) reconstruction and BIM. The approach enabled automated and comprehensive data collection, accurate BIM modelling of existing structures, planning of demolition sequences, assessment of safety risks, and precise calculation of CDW volumes and costs. By integrating these technologies, the framework improved efficiency, reduced environmental impact, and supported informed decision-making throughout the demolition process (Hu *et al.*, 2022).

The “appropriateness” of smart buildings refered to their value, aesthetics, adaptability, and ability to deliver useful benefits. The selection of suitable technologies was determined by how well it contribute to achieving functional, structural, technological, social, economic, and environmental objectives. Research by F.M. Abo-Elazm & S.M. Ali (2017) on the Beijing Water Cube established criteria for evaluating the appropriateness of smart buildings, highlighting the extent to which design depended on suitable technologies It was examined that the use of ethylene tetrafluoroethylene membrane façades and intelligent engineering systems enabled approximately 30% energy savings compared to conventional solutions for facilities of similar scale. Framework assessed environmental factors (such as natural and artificial lighting and ventilation), economic aspects (like the use of smart materials for longterm energy savings), functional integration of building systems, and social benefits including safety and occupant comfort (Fig. 3).

**Figure 3.** Beijing water cube interior
**Source:** based on F.M. Abo-Elazm & S.M. Ali (2017)

Local smart architecture used modern technologies to meet the needs of a specific community in a particular context, while supporting sustainable development for future generations. It relied on local resources and traditions, aimed to improve climate conditions, preserved cultural heritage, saved energy, and promoted sustainability (Abo-Elazm & Ali, 2017). The choice of constructions and the development of structural systems under the influence of technological progress shaped the characteristic features of architecture. Buildings were determined by the properties of available materials and technologies, while over time the emergence of new tools and materials contributed to the evolution of building forms and functions. Even traditional structures reflected the characteristics of their location, climate, and resources through design and materials. The period of the 19th-20th centuries was particularly revolutionary, as reinforced concrete, glass, and steel allowed the creation of lighter, more transparent constructions. Post-war advancements in materials science (after World War II, approximately 1945-1970s) further expanded the possibilities of architectural design, making it more universal and open to new materials and technologies (Frighi, 2022). For example, ACEEE (American Council for an Energy-Efficient Economy) conducted research, which analysed to identify key indicators of energy efficiency, resource savings, and the broader benefits of smart building technologies. These data were important for this study because it provided evidence-based insights into how intelligent efficiency measures can optimise building performance, reduce operational costs, and improve occupant comfort, which were central objectives of investigation (King & Perry, 2017).

Experts of the ACEEE report included utility programme administrators, smart technology manufacturers, and smart building practitioners. A combination of available data, facts, statistics, and practical observations was used to formulate conclusions and recommendations. The study focused on existing U.S. commercial buildings – including offices, retail properties, educational facilities, laboratories, healthcare institutions, and hospitality establishments. Residential buildings, new commercial construction, data centres, and warehouses were not included in the analysis. While multifamily buildings were not explicitly addressed, many energy-saving solutions from smart buildings could apply to their common areas. Commercial buildings were divided into two size categories: large (over 100,000 square feet, such as high-rise offices) and small to medium (100,000 square feet or less, such as a bank branch). Large buildings accounted for only 2% of the U.S. commercial building stock but occupied about 35% of the total floor area and were more likely to have smart building technologies installed. Small and medium buildings made up nearly 98% of the stock and typically lack such technologies, representing significant opportunities for implementation (Fig. 4).

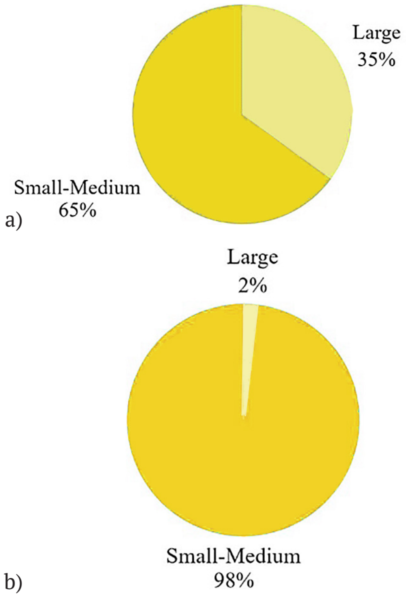

**Figure 4.** Data on commercial buildings in the U.S.
**Note:** a – number of commercial buildings; b – floor area of commercial buildings
**Source:** based on J. King & C. Perry (2017)

This study covered the entire U.S. commercial building stock, including roughly half of all buildings that were 35 years or older (constructed before 1980) and half of newer buildings (constructed after 1980). Building age was closely linked to construction types and installed equipment, which affected the kind of data that can be collected and the building processes that can be automated. All U.S. regions were included in the analysis. The South contained the largest share of commercial buildings (around 40% of the total), while the West and Midwest accounted for approximately 23% and 22%, respectively, and the Northeast made up the remaining 15%. These regional differences were significant, as each region had distinct weather patterns, income levels, building stock characteristics, and available utility programmes (Fig. 5).

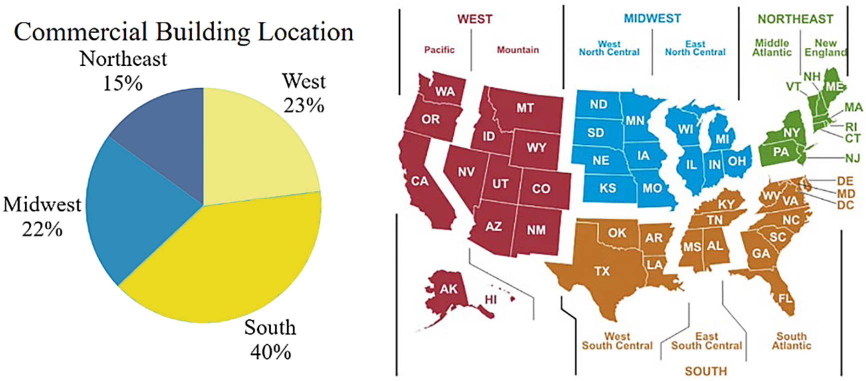

**Figure 5.** U.S. commercial building regional locations
**Source:** based on H. Ghayvat *et al.* (2015), J. King & C. Perry (2017)

These regional distributions indicated that the majority of U.S. commercial buildings were concentrated in the South and West, which correlated with higher potential energy demand due to climate conditions. So, this supported the importance of context-specific smart building strategies, as the adoption of IoT, predictive control, and energy-efficient systems must consider regional variations in occupancy, climate, and energy use. Consequently, the findings highlighted that the benefits of smart building technologies – such as energy optimisation, occupant comfort, and integration of renewable sources – may vary depending on geographic location and building characteristics. The IoT system enabled the interaction of a network of devices for collecting, exchanging, and transmitting data. In smart buildings, IoT devices automate control, reduced energy consumption, and enhanced building management efficiency. Data transmission security was ensured through the use of Constrained Application Protocol (CoAP) and datagram transport layer security protocols, which simultaneously protected information and save device energy. The application of the CoAP non-continuous awake mode further reduces energy consumption compared to other schemes. Key advantages included the integration of different building systems through IoT, protection of transmitted data with reduced energy consumption, and scalability with compatibility across various applications (John *et al.*, 2005). Smart homes for ambient-assisted living monitor resident behaviour using sensor data. Deviations from normal patterns, either unexpected or predefined as anomalies, trigger alerts for occupants. Behavioural models were generated using time-based deviation analysis, as reliable forecasting requires multiple events. The wellness prediction model had two levels: 1) lower level: raw sensor data from appliances and movement were sent to a local server via the home gateway, recording, which sensors were active; 2) upper level: software analysed data to determine optimal daily activities, using real-time intelligent recognition and classification based on sensor order and timing (Hurtado *et al.*, 2015).

The IoT enabled a network of physical objects equipped with sensors, processing units, and communication capabilities to detect events, exchange data, and interact with the environment autonomously. IoT systems supported real-time data collection and automated control, replacing traditional monitoring systems across industries. IoT generated large volumes of data, requiring connectivity, power, processing, and storage to convert it into useful information. Ensuring reliable data and network security was critical, and distributed signal processing can verify data integrity. Blockchain technology added a decentralised, transparent, and secure ledger for recording transactions and interactions. Integrating IoT with blockchain created a robust, verifiable system for managing data from connected smart devices, enabling autonomous decision-making without human intervention (Lokshina *et al.*, 2019). BIM-IoTDI (Building Information Modelling – Internet of Things Digital Infrastructure) was a layered architecture for smart-building digital twins, connecting static BIM models with dynamic IoT sensor data. Environmental data were collected by sensors and sent to storage, with static information represented as a knowledge graph and sensor data maintained in time-series databases.

The architecture provided service-oriented data access and integrated queries across static and dynamic sources. A query mediator, including components for dispatching, mapping, transforming, and postprocessing data, converted raw sensor readings into a structured format. This enabled real-time analysis, reasoning, and decision-making for smart-building digital twins (King & Perry, 2017). Big Building Data offerred various tools for building users, owners, architects, and engineering consultants. Primarily, these included data monitoring tools, which provided access to real-time metrics, historical data, and pre-calculated values. Monitoring was also useful for architects and engineers, as it allowed them to assess building and occupant behaviour. This enabled post-occupancy evaluation, energy optimisation, and improvement of user comfort. Architects can use these insights to create best practice guides and enhance their experience for future projects.

Building owners were interested in anomaly detection and predictive maintenance. By analysing historical data, standard patterns of building and occupant behaviour can be identified. Deviations from these patterns were automatically detected and can trigger alerts, such as maintenance notifications. The system can also record anomalies, their causes, and the applied solutions to suggest optimal resolutions if similar issues arise in the future. These services were currently under development (Kumar *et al.*, 2021). Energy waste in buildings often results from user behaviour. Passive approaches, like providing feedback on appliance usage, raise awareness, while active methods, such as automatically switching off standby devices, directly reduced consumption. However, existing methods often overlook user comfort and fail to handle complex contexts effectively. A context-aware system that combined passive and active strategies can optimise energy savings, while maintaining comfort. Real-time monitoring and context-awareness allowed smart buildings to adapt energy-saving measures to specific situations, potentially reducing consumption by up to 40% (Linder *et al.*, 2017).

Sensors link environmental conditions to building systems, enabling better management of energy and occupant well-being. Functional sensing systems linked environmental variables, such as temperature, to building control systems like HVAC. Z. Liu *et al.* (2023) examined sensor types, their applications, and their impact on occupant comfort and energy efficiency, and discussed how sensor data can be analysed to inform building management. The intelligent system used a deep learning model pretrained on ImageNet and retrained on a custom Room Human Counting (RHC) dataset to count occupants in real time from CCTV (Closed-Circuit Television) video streams. To handle large data volumes, Big Data technologies and deep learning libraries compatible with Apache Spark, such as TensorFlow or Caffe, are used. The predicted human count was then applied to adjust building appliances through the control system (Fig. 6).

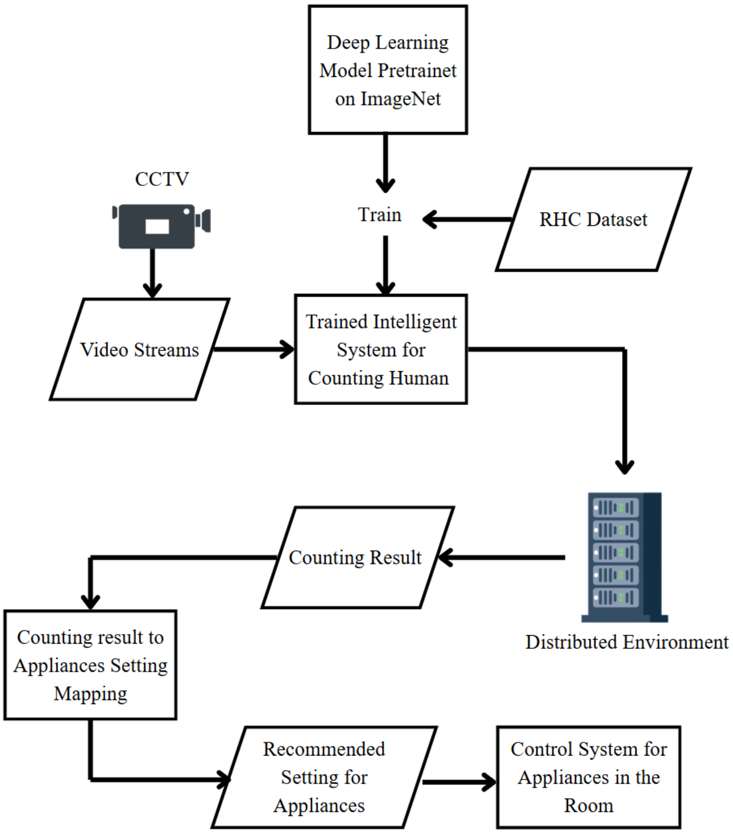

**Figure 6.** The proposed transfer learning scheme in the intelligent human counting system for smart building management

**Source:** based on B. Pardamean *et al.* (2019)

The intelligent system can be further enhanced by integrating data-driven approaches used in smart building-integrated photovoltaic (SBIPV) systems. For data-driven SBIPV, four key characteristics are identified (Fig. 7). Data sensing involved the collection of both supply-side information, such as weather conditions and roof angles, and demand-side information, including daily energy usage and prices. Collected data were then processed and analysed to identify occupant behaviour patterns and production characteristics, taking into account factors like shading effects and variable energy consumption profiles. The analysed data were subsequently used for data-driven prediction, which allowed forecasting of future trends in energy generation and consumption.

Finally, data-driven optimisation enabled efficient interaction between energy supply and demand, supporting policy guidance, the design of distributed energy systems, and peer-to-peer (P2P) energy trading.

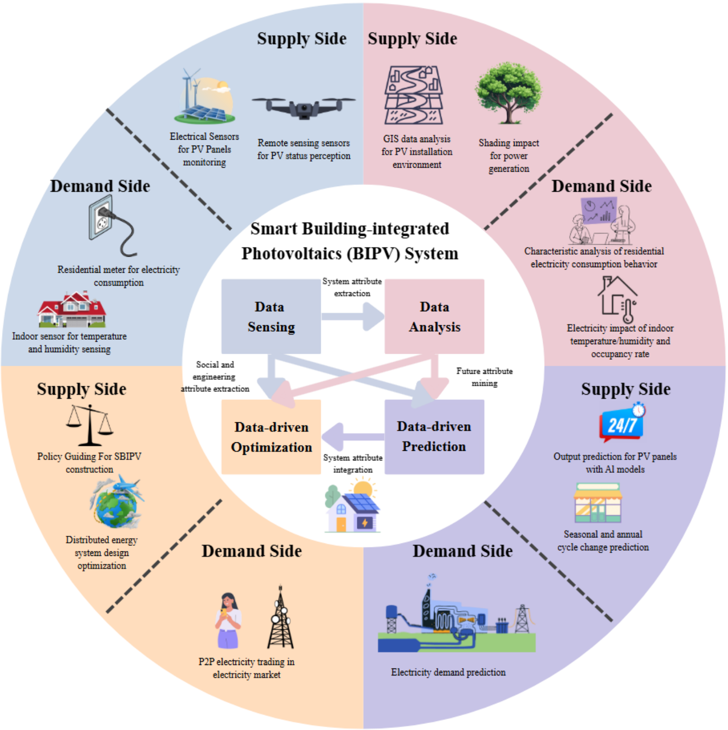

**Figure 7.** Structure diagram of data-driven SBIPV systems

**Source:** based on Z. Liu *et al.* (2023)

This integration allowed the intelligent system not only to adjust appliances based on occupant count but also to optimise energy usage dynamically based on real-time and predictive data (Qolomany *et al.*, 2019). Machine learning algorithms (supervised, unsupervised, reinforcement learning, and optimisation) were used for energy consumption forecasting, renewable energy management, intelligent control, and fault diagnostics. Special attention is given to Occupant-Centric Control (OCC) systems, which considered human presence, needs, and comfort to optimise building energy systems. The study highlighted the importance of digitalisation, automation, data collection, and analysis to enhance building efficiency and sustainability (Vattano, 2014). Future power systems required decentralised, customer-centred structures, where buildings actively supported the smart grid (SG). Buildings, responsible for a large share of urban energy use, can provide flexibility through Demand Response programmes, if integrated with advanced Building Energy Management Systems (BEMS). This study proposes a Multi-Agent System-based SG-BEMS framework, using Particle Swarm Optimisation to maximise both energy efficiency and occupant comfort. Lower-level agents process local building data, reducing complexity for higher-level agents and enabling dynamic adaptation of building systems to grid needs, such as voltage control, without compromising comfort. Simulations on a low-voltage feeder demonstrated the system's effectiveness in leveraging building flexibility to support the smart grid.

Thus, modern smart construction technologies provided integrated management of buildings and construction sites, aimed at enhancing efficiency, safety, and user comfort. H. Zhuang *et al.* (2020) noted that the use of sensors, IoT, robotics, drones, BIM, digital twins, and intelligent algorithms enabled the optimisation of workflows, increased productivity, and the promotion of sustainable development. J.L. Hernández *et al.* (2024) reviewed European buildings, noting low energy efficiency and the need for renovation. The authors discussed smart technologies like IoT, Artificial Intelligence (AI), Big Data, BIM, and Building Digital Twins, emphasising user-centred approaches and Smart Readiness Indicator (SRI). This informed research on energy optimisation, autonomous systems, and user-focused smart building design. G. Pinto *et al.* (2022) analysed transfer learning in smart buildings for energy optimisation, occupancy detection, building dynamics, and system control. The study highlighted deep learning, data-driven models, and integration of IoT, smart meters, and AI, supporting predictive control and scalable energy management. M.M.N. Shahrabani & R. Apanaviciene (2025) proposes ML to evaluate smart building integration in smart cities. Using data from 147 buildings and six algorithms (e.g., Support Vector Regression, Random Forest), reseacrhers predicted integration levels and assessed impacts on sustainability, efficiency, and resilience, guiding technology adoption strategies. S. Adhikari *et al.* (2025) reviewed BEMS, outlining components, monitoring, and control methods. Scientists showed how IoT, Renewable Energy Sources, and smart technologies enhanced energy efficiency, occupant comfort, and sustainability. G. Wang *et al.* (2024) reviewed smart building envelopes, which autonomously adapted to environmental changes, while providing insulation, protection, and structural support. The study covered types, optimisation methods, and technologies like smart windows, dynamic insulation, and Phase Change Materials, supporting energy efficiency and indoor comfort. E. Rescorla & N. Modadugu (2012) reviewed Datagram Transport Layer Security version 1.2, highlighting its role in providing secure communication over unreliable datagram-based protocols like UDP, while maintaining confidentiality, integrity, and authentication. Researchers emphasised its applicability in real-time communication systems, sensor networks, and IoT environments, offering security guarantees similar to TLS without needing a reliable transport layer. Z. Shelby *et al.* (2014) examined the CoAP, noting its efficiency in enabling machine-to-machine communication in IoT environments. Scientists emphasised CoAP's small message sizes, use of UDP, and support for asynchronous exchanges and multicast communication, making it ideal for sensor networks, smart homes, and smart buildings. Thus, the analysis of contemporary research demonstrated that smart buildings evolved from isolated automation solutions toward fully integrated, adaptive, and data-driven systems. The combination of IoT infrastructure, digital twins, ML algorithms, and intelligent materials enabled the creation of buildings capable of autonomous decision-making and continuous performance optimisation. The results confirmed that effective smart building implementation required not only technological integration but also a comprehensive evaluation framework that balanced energy efficiency, user comfort, sustainability, and operational resilience.

## CONCLUSIONS

Smart buildings represented a transformative paradigm in architecture, combining automated systems, real-time data analysis, and intelligent control to create energy-efficient, sustainable, and occupant-friendly environments. The analysis of experimental projects demonstrated that intelligent environments enhanced user comfort, reduced resource consumption, and improved operational efficiency. Data from analysed projects showed how the integration of IoT devices, machine learning algorithms, and building management systems enabled buildings to operate autonomously, anticipate occupant needs, and optimise energy use. Case studies of smart building-integrated photovoltaic systems highlight how predictive analytics and context-aware energy management allow dynamic adaptation to real-time conditions, reducing energy waste and integrating renewable energy sources efficiently. The Beijing National Aquatics Centre ("Water Cube") demonstrated that the use of ethylene tetrafluoroethylene membranes and intelligent engineering systems enabled energy savings of approximately 30% compared to traditional constructions of similar scale. Also, it was analysed that that the adoption of intelligent management systems can reduce building energy consumption by 10-30%, depending on building type and level of digital integration. The use of digital twins, building management systems, robotics, drones, and advanced sensors in construction and facility management improved planning, monitoring, maintenance, and operational optimisation, contributing to safety, productivity, and environmental sustainability. Overall, smart buildings not only improve occupant comfort and resource efficiency but also support the development of sustainable and intelligent cities, providing a scalable and replicable model for modern urban environments. Their adoption, combined with ongoing technological innovation, was essential for advancing energy-efficient architecture and sustainable urban planning. Future research should prioritise the development of unified evaluation frameworks that combine environmental, technological, and operational indicators to enhance adaptability, resilience, and long-term sustainability.

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## CONFLICT OF INTEREST

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**Руслан Мінченков**
Аспірант
Одеська державна академія будівництва та архітектури
65029, вул. Дідріхсона, 4, м. Одеса, Україна
https://orcid.org/0000-0003-1635-8317

# Архітектура сталого майбутнього: розумна будівля як синтез технології та природи

**Анотація.** Метою цього дослідження було провести всебічний аналіз технологій розумних будівель та їх інтеграцію в стале, енергоефективне та інтелектуальне урбаністичне середовище. Розумні будівлі розглядалися як системи, що поєднували автоматизовані рішення для опалення, вентиляції, кондиціонування повітря, освітлення, затемнення, безпеки та управління інженерною інфраструктурою, координовані через системи управління будівлею і реалізовані за допомогою технологій IoT, датчиків та актуаторів. Такі системи збирали дані в реальному часі, що дало змогу використовувати прогнозну аналітику, адаптивне управління та енергетичну оптимізацію. Проаналізовано методи машинного навчання, зокрема навчання з учителем, без учителя, підкріплення, нечітку логіку та стохастичну оптимізацію, для прогнозування енергоспоживання, управління відновлювальними джерелами енергії, інтелектуального контролю та діагностики несправностей. Досліджено системи контролю, орієнтовані на мешканців, які враховували наявність людини, її уподобання та комфорт, дозволяючи динамічно коригувати режими роботи будівлі та використання енергії. Була проаналізована інтеграція розумних будівель з розумними мережами на основі вдосконалених систем управління енергоспоживанням будівель, що дозволяли брати участь у програмах реагування на попит, регулюванні напруги та управлінні розподіленими відновлюваними джерелами енергії. Досліджено інтегровані фотоелектричні системи розумних будівель і підходи, засновані на даних, для прогнозування енергогенерації та споживання в реальному часі. Цифрові технології, такі як моделювання інформації про будівлю, цифрові двійники, робототехніка, дрони, обчислення на краю та хмарні платформи, підвищували ефективність процесів проєктування, будівництва, моніторингу, експлуатації та обслуговування. Незважаючи на переваги, залишилися проблеми, пов’язані з високими витратами на впровадження, ризики кібербезпеки, питання сумісності систем та необхідність удосконаленої інфраструктури управління даними. Практична цінність цього дослідження полягає в застосуванні результатів на різних етапах архітектурної практики, включаючи проєктування нових будівель, реконструкцію та модернізацію наявних споруд, а також постійну оптимізацію операцій та управління будівлею

**Ключові слова:** машинне навчання; цифрові двійники; контроль мешканців; управління енергією; розумна мережа; оптимізація даних; сталий розвиток