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Integration of Smart Technologies into Architecture of Residential Buildings: Challenges and Prospects

Jawdat Goussous*

Department of Architecture Engineering, University of Jordan, Jordan

Abstract The rapid advancement of digital technologies and the growing demand for energy efficiency in the residential construction sector create the need to develop a theoretical framework for the integration of smart technologies into building solutions. The study aims to establish an optimal balance between technological capabilities, architectural solutions and user needs, which will provide a methodological basis for the application of smart technologies in residential construction. The study is based on a systematic analysis of scientific literature in the field of construction for the period 2020-2024 using the methods of comparative and morphological analysis. A structured model of interaction between building and technical systems is developed, considering multi-level control architectures and ensuring a balance between automation and manual control. A comprehensive methodology for assessing the effectiveness of integration is proposed, which covers technical, architectural and social aspects, including criteria for assessing the technical readiness of buildings. The synergistic effects of scaling up solutions at the level of public housing through optimisation of energy flows between buildings are identified. A system of criteria has been created to assess the effectiveness of integration at different stages of the building life cycle, considering both technical capabilities and user needs. Recommendations for the design of technical infrastructure and control systems have been developed to ensure the flexibility and adaptability of smart systems. The results of the study are of practical importance for architects and engineers in the design and modernisation of both new and existing residential buildings, as they provide a systematic approach to the implementation of smart technologies. The theoretical provisions are the basis for the further development of adaptive design methods and standardisation of the process of integrating smart technologies into housing construction.

Keywords Adaptive Design, Energy Optimisation, Predictive Control, Automated Systems, Digital Transformation, Engineering Infrastructure

AMS 2010 subject classifications 93A30, 90B50

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1. Introduction

Rapid urbanisation and technological breakthroughs are significantly transforming the requirements for residential construction. International studies indicate that residential and commercial buildings consume approximately 40% of total energy in developed countries, highlighting the urgent need for innovative solutions to improve energy efficiency [1]. In the face of global challenges caused by climate change and the depletion of natural resources, the integration of smart technologies into residential construction is the main direction of the evolution of traditional construction methods. Under the influence of digitalisation, the transformation of the living environment creates new challenges for architectural design. The need to integrate and interact with increasingly complex engineering systems and building solutions requires a rethinking of conventional approaches to the design of residential buildings. The development of flexible building solutions that can adapt to rapid technological development and

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*Correspondence to: Jawdat Goussous (Email: goussousjawdat1@gmail.com) Department of Architecture Engineering, University of Jordan. 275 Queen Rania Str., Amman, Jordan (11942).

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changing user needs should be emphasised. Thus, the digital transformation of living space is becoming not only a technological trend but also a critical condition for creating sustainable and efficient housing in the future.

Lamnatou et al. [2] analysed renewable energy systems and identified the potential for integrating smart technologies and alternative energy sources. The authors employed a comprehensive approach to analyse energy systems and developed a methodology for assessing the interaction between photovoltaic systems and smart grids, based on the dynamic aspects of energy consumption and the specifics of building solutions. Al Dakheel et al. [3] developed an innovative system for assessing the efficiency of smart buildings. This methodology is the first to establish a link between architectural solutions and the potential for smart technologies. The team of Kim et al. [4] explored new opportunities for the scalability of intelligent systems. The study covers the analysis of different levels of integration from a single building to a city block, where synergistic effects were identified.

Yang et al. [5] conducted a detailed analysis of energy consumption optimisation in residential buildings based on adaptive control. The investigated intelligent model demonstrated the reduction of heating costs by 20-25%. Particularly noteworthy is the discovery of a 30% reduction in peak loads due to phase change materials. The team of researchers Hernández et al. [6] proposed the Smart Readiness Index, which transforms the approach to assessing the readiness of buildings, accounting for technical infrastructure, energy systems, and grid integration potential. Froufe et al. [7] outlined the importance of system integration in smart buildings, where 40 % of efficiency depends on the interaction between subsystems. The researchers have developed a matrix for assessing technology compatibility that covers the physical, informational, and functional levels of integration, emphasising the standardisation of communication protocols and cybersecurity. Moeller [8] analysed a German residential complex and identified differences between technical competence and the actual implementation of intelligent systems. The adaptive control interfaces and training methodologies studied by the authors form a new paradigm of interaction between technologies and users, which is confirmed by the results of their research.

In another study, Cvar et al. [9] investigated the architecture of Internet of Things (IoT) systems for smart buildings, determining that 35% of success depends on the quality of architectural integration and 25% on the choice of communication protocols. The developed methodology included five levels: sensors, networks, data processing, applications and services for designing IoT infrastructure. The team of researchers Um-e-Habiba et al. [10] opened new perspectives on assessing the adaptability of building systems using big data and artificial intelligence. This methodology has shown a correlation between the complexity of system management and performance, and the created optimisation matrix helps to achieve the best balance between complexity and efficiency at the design stage.

However, most studies address individual technological components without creating a holistic methodology for designing smart buildings that address the interdependence of architectural, technological and social aspects. The study aims to develop a theoretical framework for the integration of smart technologies into residential buildings by identifying the optimal balance between technological capabilities, architectural solutions and user needs. This approach is intended to facilitate the development of a methodology for designing an efficient and comfortable living environment that meets modern energy efficiency and adaptability requirements. The main objectives of the study are to develop structured models of interaction between buildings and technological systems in smart buildings; to determine criteria for assessing the effectiveness of smart technology integration at different stages of the building life cycle; to create methodological recommendations for the design of residential buildings with a focus on the potential for using smart technologies.

2. Literature review

According to a study conducted by Lamnatou et al. [2], the integration of smart grids in combination with photovoltaic systems can increase the efficiency of renewable energy sources by 20-30%. The study confirms that such synergy does indeed improve the performance of these technologies. The methodology used by the authors determined that the optimal integration of smart grids and energy storage systems helps to ensure a stable energy supply, even in the context of unpredictable renewable energy generation.

Hwang et al. [11] conducted a comprehensive study of the construction sector in Singapore to identify the problems that hinder the implementation of smart technologies. The main problems identified were data and information exchange, regulatory compliance, and data ownership. Based on an in-depth analysis of the industry, the researchers proposed a comprehensive strategy to overcome the identified obstacles, focusing on the development of skilled personnel in construction. Importantly, government support is a key factor in developing the necessary skills. In addition, significant success in this area is determined by the development of effective communication mechanisms and change management in organisations. Yang et al. [12] created a holistic concept of the future development of the industry through a systematic analysis of the technological foundations of smart buildings. Important components include building information modelling (BIM) technology, IoT sensor and actuator systems, and cloud-based data analytics platforms. The researchers highlighted the integration of building automation systems with smart metering and monitoring systems. The study identified significant barriers to implementation, including technical incompatibility between systems from different vendors, cybersecurity issues, and high initial investment costs. The difficulty of integrating into existing buildings and the need for staff training were also highlighted as key organisational challenges.

Nižetić et al. [13] investigated the multifaceted potential of smart technologies in transforming the living environment. The study revealed a direct correlation between the introduction of these technologies and the increased energy efficiency of buildings. The researchers developed a methodology for assessing the impact of smart systems on the comfort of residents, optimising operating costs and anticipating maintenance. Emphasis was placed on the development of a methodology for assessing environmental impact using carbon footprint, resource efficiency and the integration of renewable energy sources as indicators.

Shahzad et al. [14] developed a comprehensive Internet of Energy (IoE) architecture for industrial applications that covers physical, communication, processing, application, and service layers. This study emphasised the importance of protocol standardisation and data protection to create effective control systems. In turn, Lawal and Rafsanjani [15] identified the key elements of successful digital transformation in residential buildings. The studied efficiency matrix identified a correlation between building solutions and the adoption of the latest technologies, paying particular attention to the scalability and adaptability of systems.

A comprehensive study by Moreno Escobar et al. [16] highlighted the synergy potential of integrating distributed energy resources in smart grids. The analysis of energy flows at the level of municipal neighbourhoods demonstrates significant potential for optimising energy consumption through load balancing. The methodology for designing integrated solutions considered the dynamic characteristics of demand and the specifics of local energy resources. Vijayan et al. [17] made a significant contribution to understanding the interaction of subsystems in smart buildings by developing a multi-level classification, emphasising the critical role of the quality of physical infrastructure integration. The study of Huseien and. Shah [18] has shown that high-speed networks change the efficiency of energy management systems, while the introduction of 5G technology opens new opportunities for real-time scenarios, ensuring reliable integration of various subsystems.

Panteli et al. [19] proposed a new paradigm for integrating BIM with IoT platforms, which allows the creation of digital twins of buildings with real-time data to optimise operational processes and reduce costs. The digital life cycle management methodology covered all stages from design to disposal. Other important studies were conducted by Kumar et al. [20] on the development of an energy-efficient smart home architecture through the analysis of data transfer protocols, where Constrained Application Protocol with optimised wake-up mechanisms can significantly reduce the energy consumption of sensor networks.

Hassan et al. [21] carried out a thorough analysis of the impact of the network on the evolution of urban technologies, systematising the challenges, opportunities and solutions offered by the smart city concept. The study focuses on the efficiency of implementation, infrastructure requirements, and the potential for urban system development. Emphasis is placed on the ability of the network to ensure the integration of various urban subsystems, forming a single information space.

An architectural and engineering study conducted by Kim et al. [4] determined that optimising energy flows between buildings can increase system efficiency by 15-20% in the context of the transition to the district level. In addition, the researchers concluded that the integration of energy storage systems can increase the energy autonomy of complex buildings by 25-30%. Based on a comprehensive study by Al Dakheel et al. [3], architectural design can determine up to 45% of the overall efficiency of smart systems. Researchers developed a system of more than 50 indicators covering energy, operational, and economic aspects to assess the performance of smart buildings. Aguilar et al. [22] performed a systematic analysis of the use of artificial intelligence in the intelligent management of building energy consumption to determine the potential of smart control systems. The study focuses on the use of artificial intelligence to optimise energy consumption and increase the autonomy of building systems. The proposed approach to the integration of artificial intelligence has become the basis for the creation of adaptive energy management systems.

Froufe et al. [7] created a comprehensive model for assessing smart buildings through key factors and system interconnections. This innovative approach consisted of identifying 11 key factors covering technical, operational and social aspects, ranging from technological integration and flexibility to comfort and safety. The architecture of a smart building was considered through the prism of eight key systems, including heating, ventilation and air conditioning, lighting, energy supply and security. Particular attention is paid to the synergistic effects of the interaction between different subsystems and the impact on the overall efficiency of the building. The human factor determines the effectiveness of smart system usage and the acceptance of technologies by occupants. Engaging residents through training and informational sessions enhances comfort and safety in building operation.

Singh et al. [23] conducted a fundamental study of the evolution of the smart city concept and the relationship between technological capabilities and the sustainable development of the urban environment. The developed methodology for assessing technological readiness became the basis for strategic planning of urban infrastructure development. The study showed that systemic integration of technological solutions plays an important role in the effective functioning of smart cities.

Lee and Kim [24] critically analysed smart living environments, identifying the key importance of attention to user experience. The researchers identified four dimensions of evaluation: well-being, independence, acceptability, and design. The methodology has transformed the understanding of the interaction between technology and users in the living space. Carlucci [1] streamlined the use of smart technologies in architecture by developing a detailed classification. The methodology for assessing the adaptability of building systems has become the basis for creating specific technological solutions, including adaptive facades, smart windows, and dynamic shading systems that help reduce energy consumption.

Manzoor et al. [25] identified key trends in technological change through a bibliometric analysis of digital technologies in construction. The study highlighted the growing role of BIM, augmented reality, virtual reality and other digital tools in design and construction. The potential of these technologies to increase efficiency and reduce waste in construction projects was highlighted. According to the methodology for calculating the Smart Readiness indicator developed by the European Commission [26], which assesses the readiness of buildings to implement smart technologies across nine technical domains and seven impact criteria, researchers. Hernández et al. [6] identified that only 15% of the existing housing stock in Europe can be integrated with smart systems without the need for significant modernisation. The authors identified the main requirements for technical infrastructure and energy systems necessary for the effective implementation of smart technologies. Yang et al. [5] analysed the potential for demand flexibility and cost savings through smart energy management systems in residential buildings, identifying the minimum requirements for technical infrastructure and energy systems for the successful implementation of smart technologies.

Interfaces and systems should be designed with inclusivity, accessibility, and ease of use for diverse user groups in mind. Clear visual and sensory cues, standardized controls, and ergonomic placement improve convenience and safety. Um-e-Habiba et al. [10] developed an optimisation matrix that addresses 11 key parameters of control systems, such as reliability, scalability and energy efficiency. The use of an optimised solution based on this matrix can reduce operating costs by 25-30% without compromising on high system reliability.

Smart technologies can both facilitate communication among residents and create isolation due to excessive automation. Using interactive platforms and shared digital spaces promotes community building and supports social engagement. Firas et al. [27] conducted a study on the implementation of smart technologies in the context of historical buildings, focusing on the Abu Jaber Museum in Jordan. An analysis of lighting and air conditioning issues led to the creation of a framework for integrating an automatic lighting control system into historic buildings. This framework includes Wi-Fi switches, dimmers, and three types of sensors: PIR, lux, and motion sensors. The authors also considered in detail the optimal location of these elements, placing motion sensors in the corners of rooms and at the entrance, and light sensors near windows. This can significantly improve the energy efficiency of the building while preserving its historical value. The results of the study demonstrate the potential for effective use of smart technologies to modernise cultural heritage without compromising authenticity. A study of a German residential complex conducted by Moeller [8] determined that the efficiency of smart systems can be reduced by 30-40% without considering the individual needs of users. Based on the data obtained, an adaptive control algorithm was developed that integrates the individual behaviour of residents to improve the system's functionality. This means that effective technological integration has a 30-45% impact on the process, taking into account user behaviour patterns has an impact of 25-40%, and the adaptability of control systems has an impact of 20-30%. Under these circumstances, an integrated approach is needed to implement such technologies. It is especially important to create adaptive building concepts for the effective use of innovative technologies throughout the entire life cycle of a building.

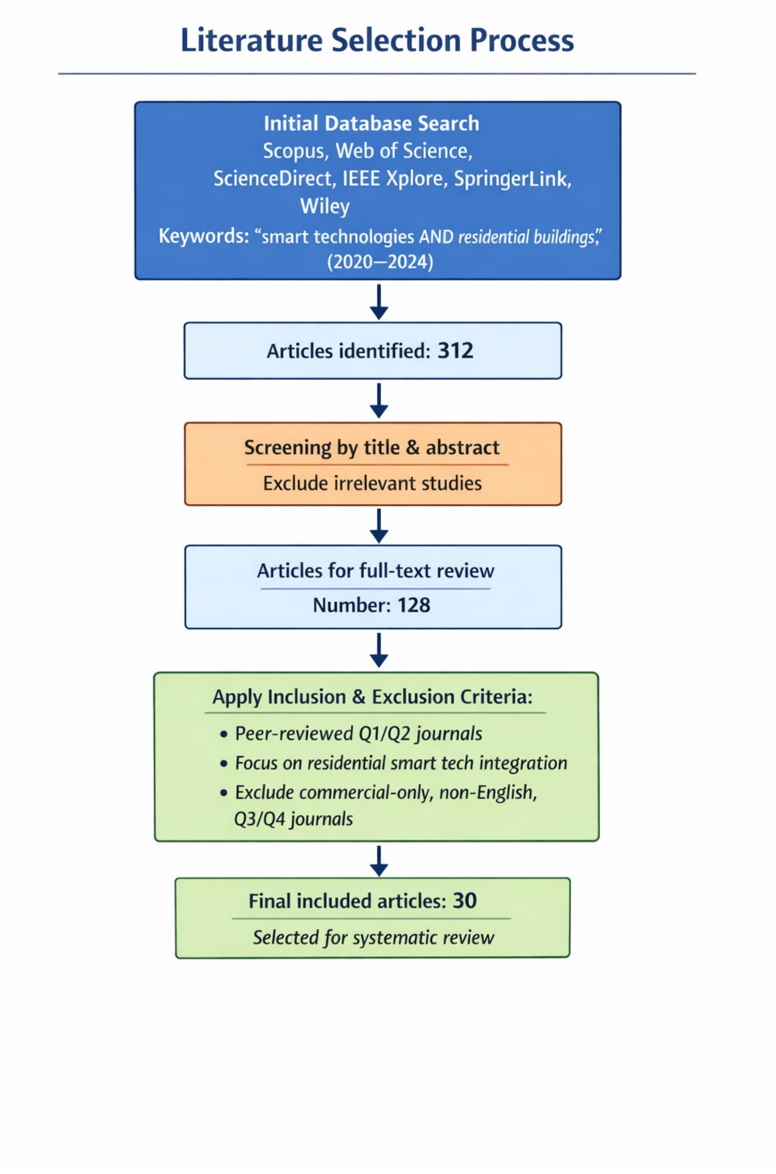
3. Materials and methods

A theoretical study with elements of systematic analysis of the processes of integrating smart technologies into the architecture of residential buildings was conducted in October 2024. This study is based on a comprehensive analysis of scientific articles from 2020 to 2024, reflecting current trends in the technological transformation of the living environment and identifying key areas for the development of the industry, considering the global challenges of digitalisation. The study is based on scientific publications of leading international architectural, engineering and technical journals indexed in Scopus and Web of Science. The literature selection for this study was conducted following systematic review principles to ensure scientific rigor and representativeness of sources. Initially, precise keywords and search strings were defined, including combinations such as "smart technologies," "residential buildings," "energy efficiency," "IoT," "building automation," "predictive control," "adaptive architecture," "BIM integration," "digital transformation in construction," and "renewable energy systems," using logical operators AND/OR to maximize relevance. Searches were performed across leading scientific databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, SpringerLink, and Wiley Online Library, covering publications from 2020 to 2024. The initial search yielded 312 articles, which were screened by title and abstract, reducing the set to 128 articles for full-text evaluation. Inclusion criteria encompassed peer-reviewed Q1–Q2 journal articles directly addressing smart technology integration in residential buildings, with quantitative or methodological results on energy efficiency, automation, or technological–architectural system interactions. Exclusion criteria included studies focused solely on commercial buildings, conceptual reviews without empirical data, publications in Q3–Q4 journals, and non-English articles. During full-text analysis, 128 articles were carefully evaluated for methodological rigor, sample representativeness, use of advanced technologies, and presence of quantitative outcomes, resulting in 30 studies being selected for systematic inclusion. A flowchart was developed to visually summarize the selection process, showing the number of articles at each stage: initial search – 312, post-abstract screening – 128, and final inclusion – 30. Limitations of this approach include the focus on Q1–Q2 journals, potentially excluding relevant emerging or regional studies, and the restriction to 2020–2024, which may omit foundational earlier research. Nonetheless, the application of explicit inclusion and exclusion criteria across multiple leading databases ensured high scientific relevance and robustness of the selected literature.

Technical documentation of implemented projects and regulatory documents on technology implementation were also analysed. The study was conducted using a variety of scientific analytical methods. The focus was on technical infrastructure, construction solutions, energy efficiency, and automation systems. Comparative analysis was used to assess the effectiveness of various technological solutions and their impact on the design, performance and energy efficiency of buildings. Systems analysis methods were used to study the interaction between the subsystems of a smart building, such as energy, information, engineering, and user subsystems. A matrix of 15 criteria grouped into the categories of technical sophistication, architectural integration, and operational efficiency was created to assess the effectiveness of integrated solutions. Morphological analysis helped to determine the optimal configuration of technical solutions for different types of housing – individual, collective and communal.

This study provides a detailed analysis of current methods for assessing the technical readiness of buildings for the integration of smart technologies. Particular attention is paid to the study of the potential for integrating automation, energy management and intelligent control systems based on the Smart Readiness Indicator methodology developed following the updated EU Energy Performance of Buildings Directive [26]. The methodology is based on nine technical domains (heating, cooling, hot water, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, monitoring and control) and seven smart building impact criteria (energy efficiency, maintenance and fault prediction, comfort, convenience, health, well-being and accessibility, occupant information, flexibility and energy storage).

Figure 1. Literature selection process.



Based on this analysis, an adapted methodology was developed that accounts for the specifics of residential construction and the integration of modern building technologies. This methodology consists of an assessment of technical infrastructure, energy efficiency potential, automation capabilities and the ability to adapt building solutions. The results were interpreted using a multi-level data analysis. The technological level involved assessing the effectiveness of individual technological solutions and their interaction. The architectural level included an analysis of the impact of the applied technologies on the design and operational properties of the facilities. At the system level, the patterns of interaction between different subsystems and their contribution to the overall performance of the building were determined. The reliability of the results was confirmed by cross-checking data from various sources and comparing theoretical conclusions with practical implementation results. The study also examined the practical application of BACnet data transfer protocols for building automation systems, KNX for lighting and climate control, and Modbus for energy systems, as well as Secure Sockets Layer (SSL)/Transport Layer Security (TLS0 security protocols, OAuth 2.0, JSON Web Token (JWT), and methods of load forecasting using long short-term memory neural networks.

The review of information sources identified key factors for the successful integration of technologies in housing construction and identified promising areas for the development of smart buildings, accounting for technological capabilities and social needs.

4. Results and discussion

4.1. The latest technologies in shaping living environments

The intellectualisation of living spaces using smart technologies has become a new trend in architecture, combining digital innovations with traditional approaches to creating living environments. This synergy creates a unique paradigm where technological saturation is an integral part of architectural solutions. The main principle is to integrate physical and digital space into a single ecosystem. Operational capabilities are optimised through virtual building modelling, constantly updated in real-time. This combination of physical and digital aspects creates a new way of looking at building space as a dynamic and adaptive system.

The modern technological infrastructure of housing requires a rethinking of classical engineering system design methods. Distributed computing and autonomous subsystems create a multi-level control architecture where each element works independently and is simultaneously part of a single architectural organism. The use of smart algorithms to manage energy efficiency is becoming increasingly relevant. A system trained based on user behavioural patterns strikes a balance between comfort and resource savings, allowing for the prediction and optimisation of energy consumption.

The integration of renewable energy sources becomes not only a technical solution but also part of a sustainable development strategy. The flexibility and adaptability of the building are achieved using a modular system. Dynamic elements that respond to changes in the environment and the needs form living and sensitive organisms that evolve with the occupiers. The security paradigm in smart architecture goes beyond the usual understanding of this concept. An integrated multi-level cybersecurity system is complemented by physical access control to create a comprehensive cycle. Resilience and autonomy of critical components are key elements of the system. The psychological comfort of users is becoming a central element of smart space. Research into the cognitive aspects of interaction with the environment contributes to the creation of a natural and intuitive control interface. At the same time, technical saturation should not contribute to alienation or loss of control.

The economic model of smart buildings is moving from simple costing to complex asset management systems. Data monetisation, personalised services and operational process optimisation are opening new revenue streams and changing the traditional view of the housing economy. A responsible attitude to the environment is realised through a closed cycle of resource consumption. Smart monitoring and management systems help minimise the environmental impact of buildings and transform them from passive consumers of resources to active participants in urban ecosystems.

The modern architectural paradigm is undergoing a transformation that reflects a deep combination of design solutions and digital technologies. This approach is revolutionary in shaping living spaces, where architecture is closely intertwined with smart infrastructures. The integration of the physical and virtual dimensions is achieved through digital building modelling, while continuous monitoring of operational parameters allows for the optimisation of functional processes and increases resource efficiency.

The infrastructure of modern residential buildings requires the introduction of decentralised management systems. This principle of decentralisation ensures the sustainability of individual subsystems while taking an integrated approach to building management. Energy efficiency in residential complexes is achieved through intelligent forecasting algorithms that, based on the analysis of behavioural patterns, help to find a balance between comfort and energy efficiency. Adaptive structural systems contribute to the flexibility of buildings, allowing spatial elements to change following external and internal factors that meet the changing needs of residents. The security of the living environment is ensured by the integration of physical and digital security systems, covering all aspects of operation – from data protection to access control.

Solutions prioritizing user diversity and accessibility in smart and digital systems involve a systematic design approach that ensures effective interaction for all users, regardless of age, physical abilities, digital literacy, or prior experience with technology. Conducting user-centered design research helps identify the specific needs of different groups, uncover potential barriers to system use, and develop interface prototypes that provide comfort, safety, and operational efficiency. Aligning usability testing protocols with international standards is a key element in ensuring high-quality interfaces. The WCAG 2.1 (Web Content Accessibility Guidelines) [28] standard defines accessibility criteria for digital content, addressing the needs of users with various physical and sensory impairments, including those with visual, auditory, or motor limitations. ISO 9241 [29] focuses on the ergonomics of human-system interaction, evaluating clarity, ease of use, efficiency, and user satisfaction during interaction with an interface. Applying these standards allows not only formal verification of interface compliance but also the systematic implementation of best practices in accessibility and ergonomics at all stages of design and testing.

Incorporating a “User Diversity Checklist” into design recommendations ensures that research findings and standard requirements are translated into practical design processes. This checklist allows designers to verify whether all user groups are considered, assess the need for specialized accessibility features, and make informed decisions to optimize interfaces. These measures enhance usability and effectiveness while promoting inclusivity, reducing social isolation for specific groups, and increasing the adoption and long-term sustainability of technologies – especially critical for complex integrated solutions in smart buildings and public spaces [30].

The design of interfaces for intelligent environments is based on fundamental research in cognitive psychology, which incorporates the peculiarities of human perception for optimal design. Smart building operating models go beyond traditional real estate valuation to create added value through personalised services. Circular economy defines the approach to managing resource flows in smart buildings, integrating them into urban ecosystems for sustainable development. Artificial intelligence technologies are opening new opportunities for living environments where control systems are capable of self-adaptation, laying the foundation for truly intelligent spaces [31].

The development of tailored recommendations for cold climates, densely built high-rise urban environments, and historical buildings requires a detailed assessment of the specific challenges and constraints of each building type. This process begins with analyzing environmental conditions, structural characteristics, and local regulatory requirements to identify appropriate smart building technologies and integration strategies. Region-specific energy optimization matrices are then developed, taking into account the availability of local renewable resources such as solar, wind, or geothermal energy, allowing for the design of systems that maximize efficiency and sustainability. Implementation relies on combining building simulation tools, energy modeling software, and sensor-based monitoring systems to ensure that the proposed solutions are technically feasible and compatible with existing infrastructures [32]. User training and post-implementation support are integrated into the deployment strategy to ensure effective long-term use, with structured workshops, instructional materials, and remote assistance offered to users who may lack technical expertise. A post-deployment support model, including routine maintenance schedules, system performance monitoring, and helpdesk services, ensures that residents can operate smart technologies safely and efficiently, thereby maintaining energy savings, comfort, and overall system reliability over time [33].

The structural model for the integration of smart technologies into residential buildings consists of three closely related levels: technological, which includes automation and control systems; infrastructure, which includes network and communication elements; and user, which provides interaction tools. The analysis of this model highlights the importance of a systemic integration approach to the successful implementation of smart solutions in residential complexes. The study uses the key criteria for assessing the European Commission’s Smart Readiness

Indicator to determine the readiness of buildings for the introduction of smart technologies [26]. The assessment methodology is based on an analysis of the efficiency of smart services in nine technical areas (heating, cooling, hot water, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, monitoring and control) and seven impact indicators (energy efficiency, maintenance and fault prediction, comfort and convenience, health, well-being and accessibility, resident information, flexibility and energy storage). The results of the assessment are aggregated into a general SRI class, which determines the degree of readiness of the building for the implementation of smart technologies. Based on this methodology, a comprehensive analysis was carried out, including an assessment of the technical infrastructure, energy systems and network integration potential, which identified the necessary areas for modernisation of the studied facilities.

4.2. Structural models of interaction between building and technological systems

Monitoring the interaction between smart home subsystems emphasises the importance of achieving an optimal balance between automation and manual control processes. According to a study by Moeller [8], an analysis of the behavioural patterns of residents of German residential complexes revealed a significant gap between the technical capabilities of smart home systems and the real needs of users. In particular, the study determined that a significant number of residents prefer different temperature conditions in different rooms, while the automation system seeks to create unified conditions throughout the entire building. The use of predictive algorithms to manage energy consumption has demonstrated high efficiency in coordinating the functioning of various engineering systems.

Kim et al. [4] showed that the integration of heat pumps with energy storage systems and photovoltaic installations can significantly increase the efficiency of renewable energy sources. The key feature of such integration is the use of smart inverters to optimise the balance between energy production and consumption, as well as the use of energy storage systems to smooth out peak loads. Intelligent control algorithms ensure the coordinated operation of all system components, considering the current needs of consumers. The use of machine learning methods to predict energy consumption has made it possible to optimise equipment operation modes, considering weather conditions, fluctuations in electricity prices and behavioural trends of residents. The study of the architecture of IoT systems highlighted the need to ensure five key functionalities: object identification, data collection from sensor equipment, reliable communication, distributed computing tasks and semantic information processing. The development of mechanisms for collecting data at the end-device level was essential, which reduced the load on the network infrastructure and increased the autonomy of the local control system.

To achieve comprehensive protection, experts recommend implementing standardised interaction protocols along with a multi-layered security system. This includes protection at the physical hardware level, network security using SSL/TLS protocols, and the application layer using OAuth 2.0 and JWT tokens. The use of blockchain technology and smart contracts to ensure data integrity establishes a solid foundation for the development of resource-sharing services [7, 9].

The analysis showed that the integration of individual buildings into local power grids with the possibility of mutual energy exchange can significantly improve the efficiency of optimising electricity consumption and the reliability of supply. The integration of energy storage systems with photovoltaic installations has significantly increased the energy autonomy of buildings. The use of materials with phase transition in the structural elements of buildings, combined with intelligent control, enabled efficient management of heat flows and optimisation of energy consumption for heating [1].

The system should be organised hierarchically with three key layers: physical, including sensors and actuators; network, responsible for the communication infrastructure; and application, which includes control and analysis systems. This is necessary to ensure effective interaction between all components, as shown in Table 1. Standardisation of interfaces and communication protocols is critical to ensure interoperability between different building subsystems.

Table 1. Structure of the technical infrastructure of smart buildings

Level of infrastructure	**Components**	**Functional purpose**	**Standards**
Sensors	Temperature, humidity, CO_2, presence sensors	Collecting data about the environment	ISO 16484
Network	WiFi, BLE, 5G	Data transmission	IEEE 802.11
Data processing	Edge controllers, cloud services	Analysis and management	IEC 63180
Interface	Mobile applications, control panels	User interaction	ISO 27001

Note: BLE — Bluetooth Low Energy; Edge — edge computing.
Source: created based on Cvar et al. [9].

Table 2. Matrix of criteria for assessing the effectiveness of smart technology integration

Evaluation category	**Criteria**	**Performance indicators**
Technical excellence	1. Reliability of control systems	Continuous operation time >98% of the time
Technical control systems	2. Quality of interaction between subsystems	Response latency <100 ms
Automation and Control	3. Scalability of solutions	Possibility of expansion by 30%
Information security	4. Cybersecurity	Multi-level data protection
Sustainability of systems	5. Fault tolerance	Automatic recovery
Architectural integration	1. Infrastructure compatibility	Minimal design changes
Planning solutions	2. Aesthetic integration	Preserving the architectural appearance
Design features	3. Impact on construction	No negative impact
Flexibility of solutions	4. Adaptability to change	Possibility of modernisation
Maintenance	5. Ease of maintenance	Easy access to equipment
Operational efficiency	1. Energy efficiency	Reduction in energy consumption by 20–30%
Comfort and convenience	2. User comfort	Positive feedback >85% of the time
User interaction	3. Intuitiveness of control	Training time <2 hours
Economic metrics	4. Economic efficiency	Recoupment <5 years
Environmental safety	5. Eco-friendliness	Compliance with environmental standards

Note: performance indicators are based on the analysis of successful implementations of smart technologies.
Source: created by the author based on Al Dakheel et al. [3], Froufe et al. [7], Um-e-Habiba et al. [10].

An analysis of the communication infrastructure demonstrated the importance of standardising protocols for data transfer between subsystems, such as BACnet for building automation, KNX for lighting and climate control, and Modbus for energy systems, to ensure effective interaction between different subsystems. The introduction of 5G technology opens new opportunities for real-time management scenarios with minimal latency and high bandwidth. Studies of user interfaces have shown the need to create intuitive management and data visualisation tools. The development of adaptive interfaces that accommodate individual user preferences has increased the level of technology adoption and the efficiency of use in everyday life [3, 18].

The analysis of the implementation of smart technologies in residential buildings has identified key parameters that determine the success of the integration of technological solutions. To systematise these parameters, a matrix of criteria was developed, which allows for a comprehensive assessment of the effectiveness of the technical, architectural and operational aspects of smart technologies (Table 2).

The matrix identifies three categories of criteria as key. The technical excellence category focuses on the reliability and security of the systems. Architectural integration analyses how harmoniously these technologies are integrated into the existing infrastructure. Operational efficiency focuses on the practical aspects of using the systems. Specific performance indicators have been defined for each criterion and can be used to objectively assess the success of smart technology implementation.

Models for financing and policy recommendations play a critical role in the successful implementation of smart building technologies. Public–private partnerships can provide a flexible framework, combining government incentives with private sector investment to reduce upfront costs and share long-term risks. Subsidies, tax credits, and low-interest loans for energy-efficient installations encourage adoption, particularly in residential and social housing projects. Performance-based financing, where repayment is linked to realized energy savings or operational efficiency, ensures financial viability and motivates continuous system optimization. Policy measures should include clear regulatory standards for interoperability, data security, and system certification, which reduce uncertainty for investors and developers. Additionally, national and local governments can promote knowledge-sharing platforms and pilot projects to demonstrate feasibility, increase stakeholder confidence, and accelerate adoption across different market segments. Integrating these financial models with supportive policies helps align economic incentives with technological goals, ensuring sustainable deployment and long-term benefits of smart building solutions.

4.3. Effectiveness of integration measured by defined criteria

A comprehensive analysis of the integration processes of smart technologies contributed to the development of a systematic methodology for assessing performance based on the Smart Readiness Indicator. A study of the European Building Fund conducted by Hernández et al. [6] revealed a significant gap in the technological readiness of buildings: only 15% of existing facilities are suitable for full integration of smart systems without the need for major modernisation. This situation has led to the need to develop a system of criteria covering technical infrastructure, energy systems and grid integration potential (Table 3).

Table 3. Security criteria for smart systems

Protection level	**Security measures**	**Support technologies**
Physical	Access control to equipment Intrusion detection systems	Biometric authentication Smart cards, video surveillance
Network	Data encryption Protection of communication channels	SSL/TLS protocols
Applied	Access control Activity monitoring	OAuth 2.0, JWT tokens Intrusion detection systems

Source: created by the author based on Froufe et al. [7], Cvar et al. [9], Kumar et al. [20].

The analysis of the security system pointed to the need to implement multi-level protection. A review of existing security practices and standards resulted in a structured set of security standards, as presented in Table 3. An important component was the need for an integrated approach that includes physical security, network security and application security.

An analysis of the technical infrastructure identified four critical components: communication networks, sensor systems, control systems, and interaction interfaces. According to a study by Cvar et al. [9], architectural systems should enable the phased introduction of new technologies. This requirement is confirmed by the performance indicators shown in (Table 4). The scalability of solutions is particularly emphasised since the use of a modular architecture can reduce the cost of further modernisation by 40-60%.

Table 4. Key performance indicators for the integration of smart technologies

Evaluation aspect	**Criteria**	**Performance indicator**
Energy efficiency	Reduced energy consumption	20–30% (HVAC systems)
	Optimisation of peak load	Up to 98.5% displacement
Technical infrastructure	Network efficiency	Reduction in energy consumption by 30.86%
Architectural integration	Overall efficiency impact	45% dependence on the quality of design solutions

Note: HVAC — heating, ventilation and air conditioning systems.
Source: created by the author.

The analysis of system processes for the integration of technical and building systems emphasises the importance of using a multi-level control architecture, including a sensor layer for data collection, a network layer for information transmission, and an application layer for processing and management. The following results were obtained from the study. To rationalise these results, three key performance indicators were developed: energy performance (energy consumption in kWh/m2 and renewable energy use), technical performance (system response time and equipment reliability), and building performance (planning flexibility and retrofit potential).

Energy efficiency analysis covers the entire energy transformation process from generation to final consumption. Lamnatou et al. [2] addressed the interaction and relationship between the integration of renewable energy sources and energy storage systems. Table 5 presents a summary of the potential of various technologies to optimise the use of energy resources, with an emphasis on predictive control algorithms that affect the overall efficiency of the system.

Table 5. Energy optimisation in smart buildings

Technology	**Savings potential**	**Implementation features**
Phase change materials	2–30%	Integration into structural elements
Predictive HVAC control	15–25%	Machine learning algorithms
Photovoltaic systems with storage	Up to 60%	Smart inverters, balancing
Lighting automation	20–30%	Presence detectors, natural light

The analysis of the data presented in Table 5 shows that the introduction of predictive energy management algorithms, such as machine learning methods, in particular the use of long short-term memory neural networks for load forecasting and genetic algorithms for mode optimisation, contributed to energy savings for HVAC systems. These results confirm the effectiveness of using intelligent control systems to optimise energy consumption in buildings.

A study conducted by Moeller [8] determined that traditional automation algorithms, such as PID control and fuzzy logic, do not address individual user preferences. To solve this problem, the integration of self-learning machine learning-based algorithms that can adapt to the needs of residents can be suggested. Retrofitting existing buildings can be done by updating the software of control systems and installing additional temperature sensors in each room. These findings highlight the need for adaptive control interfaces that can address individual user preferences.

Architectural integration is assessed based on the impact of technological solutions on the functional and aesthetic properties of a building. Al Dakheel et al. [3] developed a comprehensive system that includes more than 50 indicators to assess the integration of smart technologies. The system incorporates energy efficiency indicators, such as heat pumps, light-emitting diode, and smart meters, as well as operational characteristics, such as building management system, and economic aspects. Froufe et al. [7] proposed a matrix for assessing technology compatibility. The matrix provides a systematic approach to assessing technology compatibility through the interconnection of eleven key factors, including system reliability, solution scalability, and energy efficiency. Its practical value lies in the ability to optimise the balance between management complexity and performance at the design stage, which can reduce operating costs by 25-30% without compromising system reliability.

Froufe et al. [7] created a comprehensive model for assessing smart buildings through key factors and system interconnections. This innovative approach consisted of identifying 11 key factors covering technical, operational and social aspects, ranging from technological integration and flexibility to comfort and safety. The architecture of a smart building was considered through the prism of eight key systems, including heating, ventilation and air conditioning, lighting, energy supply and security. Particular attention is paid to the synergistic effects of the interaction between different subsystems and the impact on the overall efficiency of the building. Of particular interest is the assessment of the flexibility of the planned solutions and the ability to adapt to future technological requirements. The economic efficiency was analysed using a comprehensive life cycle analysis of buildings.

Talebi et al. [34] conducted in eight residential complexes in Germany, achieved an 8.3% reduction in electricity costs due to optimised energy consumption and a 2.6% reduction in peak loads due to participation in demand-side management programmes. These results are in line with the data presented in Figure 1, which shows a comparative analysis of the effectiveness of smart technologies in different types of housing. The safety criteria cover three main levels of protection, as detailed in Table 2. Kumar et al. [20] developed an optimised architecture that reduces energy consumption by 30.86% while providing a high level of security through a comprehensive analysis of data transmission protocols.

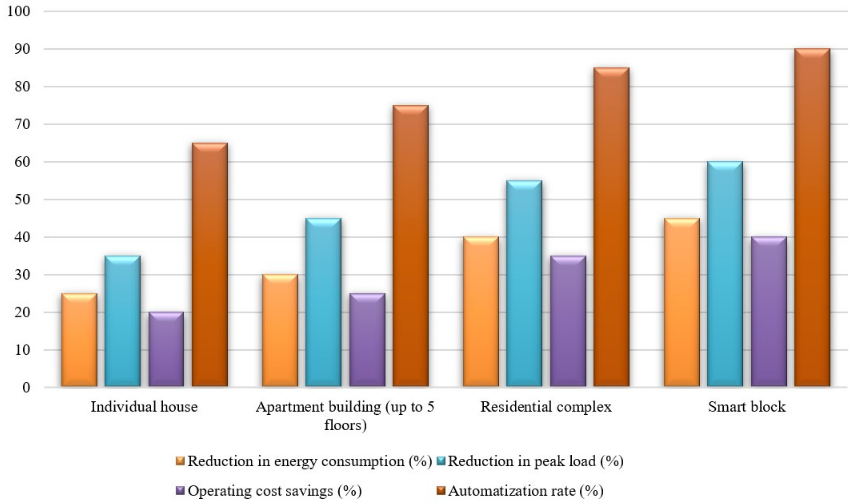


Figure 2. Efficiency of smart technologies implementation in different types of residential buildings.

Note: the level of automation reflects the degree of coverage of the building by smart control systems.

The environmental assessment criteria included an analysis of the environmental impact of the technologies. Hui et al. [35] identified the potential of smart technologies to reduce the carbon footprint of buildings by optimising energy consumption and integrating renewable energy sources. Life cycle assessment of materials and equipment is an important component of the overall efficiency assessment methodology.

4.4. Design guidelines

At the design stage, the need for flexible planning solutions that allow for the integration and modernisation of technological systems throughout the entire life cycle of buildings was identified. Providing the appropriate infrastructure at the design stage reduces future retrofit costs by 40-60% and increases the overall efficiency of the system [7].

The design of the technical infrastructure requires a special technical room with separate cable ducts for power and low-current networks, which occupies 2-3% of the total building area. It is recommended to install temperature sensors at a height of 1.5 metres and motion sensors at a height of 2.1-2.4 metres to optimise the efficiency of the monitoring system. Of particular importance is the development of a monitoring system that includes three levels of data collection: primary collection, processing on devices, and storage in the cloud. The study highlighted the importance of implementing BACnet protocols for building automation, KNX for lighting and climate control, and Modbus for energy systems. Unity of control is ensured by an open architecture for the integration of different subsystems.

Integrating renewable energy sources requires a holistic view of energy system design. The study demonstrates the effectiveness of combining photovoltaic installations with smart inverters and energy storage systems. Specialised algorithms optimise the balance between energy consumption and production, which contributes to the energy autonomy of buildings [7, 9].

The design of user interfaces should be based on the principles of intuitiveness and adaptability. The study highlights the need for mobile applications with simple interfaces, voice control and real-time visualisation of energy consumption. All systems must have a manual control function as a backup. The security system should cover three levels of protection: physical (device protection), network (data encryption, firewalls) and application (user authentication, access control). To ensure the highest level of personal information protection, the AES-256 encryption can be recommended. This technology uses a 256-bit key and 14 rounds of encryption, which provides a high level of cryptographic strength, and it is also suggested to store confidential data locally [9, 24].

An important aspect of the design is to ensure the scalability and adaptability of the system. It is recommended to use a modular architecture that can be used to add new functionality without significantly reconfiguring the existing infrastructure. It is important to provide a network bandwidth reserve of at least 30% for expansion. Monitoring and diagnostic systems should support predictive maintenance by continuously analysing equipment operating parameters such as temperature, vibration and power consumption, and predict failures using machine learning techniques.

It is recommended to introduce automatic systems for fault diagnosis and forecasting the technical condition of equipment using big data analysis and machine learning [5]. According to research, effective design of smart buildings requires an integrated approach that covers architectural, technical and operational aspects. A key element of success is to ensure a balance between the technological complexity of the system and ease of use. This is achieved through the introduction of adaptive interfaces and intuitive control systems: BACnet Web Interface for controlling engineering systems, KNX Home Assistant for lighting automation and climate control, and Modbus HMI for energy management.

The analysis of the correlation between architectural solutions and the efficiency of intelligent systems reveals a deeper dependence than was demonstrated in previous studies. A research team led by Al Dakheel et al. [3] determined that the influence of the architectural concept on the effectiveness of technical solutions is 45%. However, these results indicate the long-term nature of this impact due to potential future upgrades. In particular, addressing the requirements for technical infrastructure at the design stage can reduce subsequent modernisation costs by almost half.

In the area of energy efficiency, the findings significantly extend the results of previous studies. The methodology of Lamnatou et al. [2] is based on a detailed analysis of the energy flows of a building, using dynamic modelling and optimisation of equipment operation. The key conclusion is the importance of intuitive control through web interfaces and mobile applications that provide users with convenient interaction with smart systems. The team of researchers Um-e-Habiba et al. [10] revealed new perspectives on assessing the adaptability of building systems using big data and artificial intelligence. The researchers have developed an optimisation matrix of 11 parameters, including system reliability, scalability of solutions, and energy efficiency, which allows them to find the optimal balance between management complexity and performance.

The issue of security in the context of smart buildings requires a rethinking of traditional approaches. The methodology for assessing the technical readiness of buildings developed in this study significantly improves the five-level approach proposed by Cvar et al. [9]. While the researcher's method focuses on the technical characteristics of the IoT infrastructure, such as sensors, networks, data processing, applications, and services, the new approach expands the assessment to include the integration potential of existing systems, scalability, compliance with interoperability standards, and ease of further upgrades. This enables a more comprehensive assessment of a building's readiness for smart technologies.

Hernández et al. [6] developed a system for assessing operated buildings that consider the adaptability of architectural solutions and the potential for modernisation, which were previously overlooked by researchers. Analysis of user experience confirmed and extended the conclusions by Lee and Kim [24]. The methodology for developing intelligent environments is based on four interdependent dimensions, each of which has specific weighting factors that determine the overall effectiveness of the system. The first of these is well-being, which accounts for 30% of the total score and includes indicators of the safety of the living space along with the parameters of the physical and psychological comfort of residents. The second dimension, independence, is assessed at 25% and considers the level of automation of the systems and intuitiveness of use. The third aspect, acceptability, also has a weighting of 25% and reflects the quality of the user experience and functionality of the implemented solutions. The fourth, design, with a weighting of 20%, assesses the ergonomics and aesthetic integration of technological solutions into the architectural environment.

System integration has become a critical success factor, confirming the position of the Froufe et al. [7]. The development of integration mechanisms forms a single interconnected system that combines open data exchange protocols, such as BACnet, KNX and Modbus, with specialised gateways for intersystem interaction. This is achieved through the creation of a centralised control system with a unified web interface and the use of adaptive control algorithms based on machine learning. This integrated approach allows for maximum efficiency in the interaction of all smart home subsystems.

An analysis of international experience in implementing smart technologies indicates significant variations in approaches due to the specific climatic conditions of the regions. In countries with hot climates, a study by Awada et al. [36] found that the key to achieving efficiency is the integration of smart systems in combination with traditional architectural solutions, such as natural ventilation, passive cooling and optimal building orientation. This integrated approach reduces energy costs for air conditioning systems by 35-40% compared to buildings where innovative technologies are implemented without considering local building traditions. Important conclusions were drawn from the study of methods for modernising historic buildings. The experience of integrating automated systems into architectural monuments in the Middle East shows the effectiveness of local microgrids and decentralised microclimate control systems. This approach is complemented by the city block-level scaling strategy developed by Javed et al. [37], which serves as a methodological basis for ensuring balanced modernisation without losing the authenticity of historic districts.

The study identified three key areas for the integration of smart technologies into residential buildings. The first area relates to the development of a comprehensive assessment system that goes beyond conventional technical indicators to include socio-economic indicators and user experience factors. The second emphasises the creation of an adaptive design methodology that addresses not only current requirements but also needs for future retrofits. The third area focuses on assessing and enhancing the synergistic effect of integrating various smart systems into a single technological complex. To effectively integrate smart building systems, design guidelines should be translated into actionable steps for architects, engineers, and contractors. Cable management must be specified in detail. Instead of simply stating "separate conduits," provide minimum conduit dimensions, recommended materials (e.g., fire-resistant PVC or metal), and standardized layouts for different building types. Include instructions for routing power and data lines to avoid interference, maintain accessibility for maintenance, and ensure compliance with safety standards. A step-by-step procedure for installation, including distances from walls, floors, and ceilings, helps guarantee uniform implementation across multiple projects. Sensor placement should be clearly defined with technical specifications. Rather than recommending only height ranges, indicate exact distances from walls, ceilings, and other structural elements, as well as optimal orientation for environmental detection. Specify integration points with HVAC (Heating, Ventilation, and Air Conditioning), lighting, and security systems to ensure accurate readings and efficient control. Provide diagrams or templates showing sensor layouts in relation to furniture, ductwork, and electrical systems. These examples help teams visualize placement, reduce errors, and maintain the functionality of both smart and conventional building systems. Sntegration into overall architectural planning should be systematized. Provide methods to incorporate cable routing, sensor positions, and control devices into floor plans, schematic diagrams, and system overlays. Include sample plans for different residential typologies single-family houses, multi-unit apartments, and high-rise buildings demonstrating practical application of guidelines. By following these structured steps, design teams can implement smart systems reliably, avoid conflicts during construction, and ensure that buildings meet both functional and user-centered requirements, leading to safer, more efficient, and user-friendly living environments.

Addressing accessibility issues, regional infrastructure gaps, and alignment with local policy frameworks can be achieved through a combination of stakeholder engagement, regulatory adaptation, and phased implementation strategies. Collaborative workshops with local authorities, urban planners, and community representatives help identify critical accessibility barriers and infrastructure deficiencies, enabling tailored deployment plans for smart technologies in underserved regions. Financial models such as public–private partnerships, green bonds, and incentive-based subsidies can support the adoption of intelligent systems, particularly in areas where upfront investment costs are high. Policy recommendations include the creation of flexible regulatory guidelines that encourage innovation while ensuring safety and interoperability, as well as pilot programs to demonstrate economic and social benefits. Implementation pathways may involve staged rollouts, starting with high-priority buildings or districts, combined with real-time monitoring and feedback mechanisms to iteratively refine the deployment. Training programs for local staff and residents, along with community engagement platforms, ensure that smart technologies are accessible, effectively used, and socially accepted, fostering long-term sustainability and integration within local governance frameworks.

4.5. Challenges and barriers to the implementation of smart technologies in residential buildings

The implementation of smart technologies in residential buildings faces a range of technical, economic, and social challenges that can significantly influence the effectiveness and scalability of these solutions. From a technical perspective, integrated building systems are highly susceptible to cybersecurity vulnerabilities, including unauthorized access, data breaches, and manipulation of critical control subsystems such as HVAC, lighting, and energy storage. The complexity increases when multiple subsystems from different vendors are combined, which can create incompatibilities in communication protocols and security standards. Maintaining updated security protocols, such as SSL/TLS for network encryption, OAuth 2.0 and JSON Web Tokens for application access, and secure firmware updates, represents an ongoing practical challenge. Furthermore, system reliability can be affected by network failures, sensor malfunctions, and insufficient redundancy in multi-level control architectures, which may compromise both operational efficiency and occupant safety [38]. Predictive algorithms and AI-driven management systems require accurate, high-quality data; any disruptions or inaccuracies in data collection and processing may reduce the performance and trustworthiness of smart systems. Enhancing cybersecurity in smart building systems involves the systematic identification of potential threats and the implementation of proactive management plans to mitigate risks. This process begins with developing detailed threat models that map possible vulnerabilities across integrated building systems, including IoT devices, HVAC, lighting, and access control networks. By analyzing these threat scenarios, stakeholders can prioritize risks based on likelihood and potential impact, allowing targeted allocation of security resources. Proactive security management incorporates measures such as regular software updates, real-time monitoring, intrusion detection, and incident response protocols, ensuring rapid detection and containment of breaches. Additionally, employee and resident training programs are integrated to raise awareness of cyber risks and promote secure behavior in system interactions. Overall, this approach not only strengthens technical resilience but also builds user trust, supporting safer and more reliable operation of smart building technologies [39].

Economic barriers constitute another major factor affecting adoption. High initial investment costs, ongoing maintenance, and the complexity of retrofitting existing buildings often limit the feasibility of smart technologies, particularly in social housing projects or markets with constrained budgets. Detailed life-cycle cost analysis is necessary to assess the total cost of ownership, including energy savings, equipment depreciation, maintenance, and eventual system upgrades. Financial models must be adapted to different market segments: luxury residential developments can justify higher upfront costs through enhanced energy efficiency, occupant comfort, and value-added services, while social housing requires cost-effective solutions with rapid return on investment. Regulatory incentives, subsidies, and public-private partnerships can partially alleviate financial barriers, but inconsistent policies across regions can complicate implementation strategies.

Social challenges are also critical to the successful deployment of smart technologies. User acceptance depends on intuitive interfaces, education, and the perceived benefits of automation; resistance may arise due to unfamiliarity with digital controls, fear of loss of control, or privacy concerns. The digital divide can exacerbate inequalities, as residents with limited digital literacy or restricted access to devices may be unable to fully utilize smart systems. Behavioral adaptation is essential: energy management and adaptive control rely on residents' predictable interaction patterns, and mismatches between user behavior and algorithmic expectations can reduce system efficiency. Additionally, ethical considerations regarding data collection, privacy, and consent must be addressed to maintain trust and social legitimacy. Overall, these challenges highlight that successful integration of smart technologies requires a holistic approach that simultaneously addresses technical robustness, economic feasibility, and social acceptance, ensuring that smart residential buildings are both efficient and user-centered [33].

Collaboration with policymakers is essential for the effective implementation of smart building initiatives, as it enables the creation of practical financial instruments and supportive regulatory frameworks. This process can involve working with local governments, urban planning authorities, and national agencies to secure grants, subsidies, or low-interest loans specifically aimed at promoting energy-efficient, connected, and sustainable building projects. Financial support may also include tax incentives for developers and homeowners who integrate certified smart devices, or public-private partnerships that pool resources for large-scale retrofitting and technology deployment. By engaging policymakers early in the planning phase, stakeholders can align project goals with existing urban development strategies and sustainability agendas, ensuring that funding mechanisms are accessible and that projects remain economically viable across different housing markets, from luxury apartments to social housing. Moreover, pilot programs funded through government-backed innovation initiatives can provide real-world evidence of cost-effectiveness and social benefits, which further justifies ongoing investment and fosters broader adoption of smart building technologies.

5. Conclusion

Theoretical studies of the integration of smart technologies in residential buildings have revealed key dependencies between the quality of building solutions and the efficiency of technical systems. The developed multi-level model of interaction between building and technical components explains how to achieve an optimal balance between automation and user control. The integration of architectural solutions into the process of implementing smart technologies has proven to be influential in almost half of the overall efficiency of a smart system. In addition, the timely installation of technical infrastructure can significantly reduce modernisation costs. The results of the study confirm the need for an integrated approach to design that considers both the technical capabilities of the system and the psychological comfort of residents. The developed methodology for assessing the technical readiness of buildings for the introduction of smart technologies has improved the existing approach by integrating not only technical but also social parameters. An analysis of the behavioural patterns of residents showed the need for flexible adaptation of automation systems to individual preferences.

The introduction of predictive energy management in multi-apartment residential buildings has shown significant optimisation potential through the coordination of energy exchange between buildings. The criteria for assessing the Smart Readiness indicator (readiness of buildings for the introduction of smart technologies) have become the basis for making informed decisions at all stages of the facility's life cycle. The structural analysis of the integration process highlighted the importance of standardising protocols for the interaction of different subsystems.

The proposed control architecture, which includes sensor, network and application layers, provides the flexibility necessary to implement new technological solutions. Particular attention was devoted to multi-level security systems that include both physical and digital aspects of building operation. The developed design methodology considers the importance of creating the right infrastructure at the initial stages, which can reduce future modernisation costs by 40-60%.

The optimal parameters of the technical prerequisites and characteristics of the network infrastructure, which allow for the gradual integration of smart systems, have been determined. The integration of renewable energy sources with energy storage systems and predictive control algorithms has provided the prerequisites for achieving a high level of energy autonomy in buildings. The main limitations of the study are the lack of universal technical and organisational solutions suitable for large-scale implementation in the residential sector, as well as the insufficient number of long-term observations of the operation of facilities with integrated artificial intelligence systems. This makes it difficult to test the proposed solutions in practice in the context of rapid technological development. The results obtained during the study created a theoretical basis for the development of a methodology for intelligent building design by constructing a system of integrated architectural and technological principles.

Further research should focus on developing principles of adaptive design, studying the cognitive aspects of the interaction between intelligent systems and users, and creating a universal methodology for assessing the effectiveness of technology integration, considering both technological and socio-psychological factors.

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