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INTEGRATION OF ARTIFICIAL INTELLIGENCE AND INTERNET OF THINGS IN SMART BUILDING SYSTEMS: A STUDY ON ENERGY EFFICIENCY AND OCCUPANT EXPERIENCE

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Annotation. The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in smart buildings represents a significant advancement in building management and urban development. In this paper we explored the transformative impact of these technologies on the built environment, examining their benefits and challenges. By leveraging real-time data collection, advanced analytics, and automated control systems, AI and IoT enable unprecedented levels of energy efficiency, occupant comfort, and operational optimization in buildings. The study discusses key applications such as energy management, predictive maintenance, and personalized environmental control, highlighting their potential to reduce energy consumption and enhance user experience.

Keywords: Smart buildings, Artificial Intelligence, Internet of Things, Energy efficiency, Building automation

INTRODUCTION

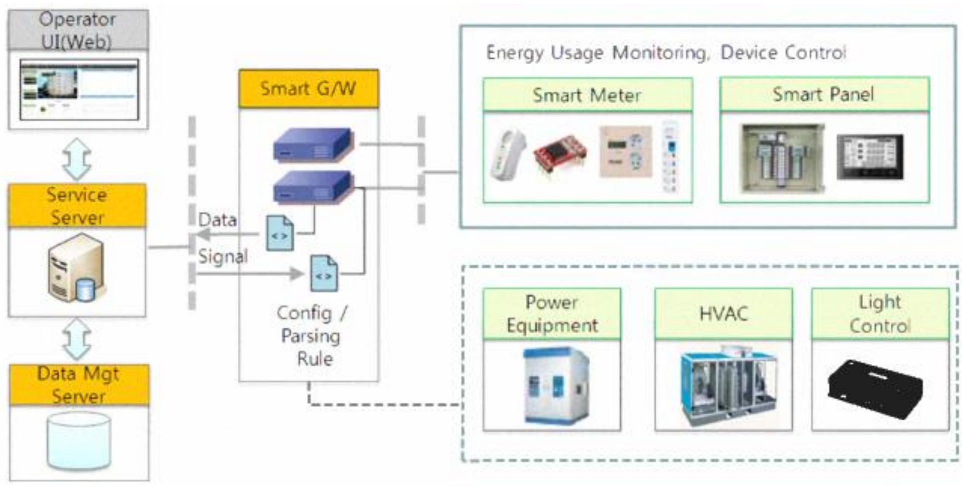
Smart buildings are a reality that is increasingly present in cities around the world. The concept of smart buildings is not new, but it has evolved mainly due to the development of new technologies, which, when incorporated, enable more intelligent resources and processes, which expand the building's capacity to operate in a more efficient, flexible, interactive and sustainable way. The concept of smart buildings has received several definitions and interpretations. Several researchers have emphasized the term intelligent building, while others have emphasized the term smart building. Smart buildings differ from intelligent buildings because they act adaptive to the occupant and not reactive (Buckman et al., 2014). Smart buildings address both intelligence and sustainability issues by utilising intelligent technologies to achieve the optimal combinations of overall experience, comfort level and energy consumption of occupant (Wang et al., 2012). Other definitions state that smart buildings are comprised of different smart environments (Mcglinn et al., n.d.), which are able to acquire and apply knowledge about the environment and its inhabitants in order to improve their experience in that environment (Cook and Das, 2007). Reducing the CO2 footprint of our cities is one of the big challenges of smart cities. Visions of smart cities, the smart grid, smart transportation, and smart buildings convey sustainable future of our cities. According to the European Union Directive on the Energy Performance of Buildings, buildings account for more than 40% of energy consumption in Europe (European Parliament, 2010). To tackle this problem, buildings are envisaged to make a transition from relatively static entities, to smart, energy efficient participants of the smart cities. From these visions, requirements emerge covering different disciplines, like Architecture, Environmental Engineering, and Information and Communication Technology (ICT).

The building sector has been considered a major contributor to fossil fuel energy consumption and carbon gas emissions. Increased heating and cooling demands in the building sector are one of the main reasons for increasing energy consumption and emissions worldwide. Energy-related emissions contribute as much as 80% of the EU's total GHG emissions, and the building sector accounts for about 40% of the EU's total final energy consumption. The U.S. Energy Information Administration (EIA) reported that the building sector's share of the global delivered energy consumption would increase from about 20% in 2018 to 22% in 2050. As the building sector is one of the largest contributors to the world's total energy use, it also offers the greatest energy savings potential compared to other sectors. According to the U.S. EIA , electricity used for appliances, lighting, cooling, heating, and other equipment in buildings is the primary source of energy consumption in both residential and commercial building sectors. Understanding energy consumption and the environmental impact of the building sector is crucial to reducing the energy and the associated issues. Various building energy-related technologies have been introduced and developed to support these global challenges of reducing building energy consumption and GHG emissions, including passive design and active system measures.

Artificial Intelligence (AI) and the Internet of Things (IoT) are two transformative technologies that are transforming various industries, including smart building systems. Artificial Intelligence refers to the simulation of human intelligence in machines that are programmed to think and learn like humans (Russell & Norvig, 2020). In the context of smart buildings, AI encompasses machine learning algorithms, neural networks, and other computational methods that can analyze data and make predictions that optimizes building operations. Embedded in AI technologies are capacity to manipulate vast amounts of data from various sources, identify patterns and making intelligent decisions to improve energy efficiency and occupant comfort (Zemtsov et al., 2021). The Internet of Things, on the other hand, refers to the network of physical objects embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet (Atzori et al., 2010). In smart buildings, IoT devices include sensors for temperature, humidity, occupancy, and energy consumption, as well as actuators for controlling various building systems. These devices form a comprehensive network that collects real-time data and enables remote monitoring and control of building operations (Li et al., 2019). The integration of AI and IoT creates a powerful synergy in smart building systems. IoT devices provide the necessary data inputs, while AI algorithms process this data to generate actionable insights and automate decision-making processes. This combination enables more efficient energy management, predictive maintenance, and personalized occupant experiences in smart buildings (Minoli et al., 2017). These technologies consider various indoor environmental factors in parallels, such as room temperature and air quality, in the design and operation to achieve a high-quality indoor environment with low energy consumption.

Over of Smart Building System

In the words of Indrawati, Yuliastri, and Amani (2017) smart building concept are the collaboration of building automation systems, integration systems, and telecommunication networks for the smart building efficiency, functionality, optimization, comfort, and economic stability. Accordingly, Buckman, Mayfield and Beck (2014) identify the smart building concept in four significant accounts, which are intelligent, enterprise, control, and construction materials, which should be adaptable to the building system to meet building progress in terms of energy efficiency, comfort, satisfaction and longevity (life cycle). The smart building concept has significantly gained prominence since its introduction in 1989 by the intelligent building institute of the United States (Ghahramani et al., 2018). Since inception, the smart building concept has progressively increased in development and practice (Olanipekun 2017). Dodge (2016) revealed that the smart building concept had been accepted globally, encouraging its development. Bao et al. (2020) opined that the clamour for smart building practices had increased worldwide. The use of smart buildings is rapidly increasing in cities around the world. The smart building concept is not new in the construction industry but has evolved due to new technologies like the internet and deep machine learning (Froufe et al., 2020). The smart building concept is a sustainable philosophy of building design, construction, and maintenance of the building life cycle, which complies with the ecosystem, economic and social life (Koko and Bello, 2020). According to Vattano (2014), the smart building concept is the brightest contemporary trend integrating the ideas of smart mobility, smart technology, smart economy, smart people, smart government, and smart environment that reduce the building practice impact on the environment in the construction industry. Attoue, Shahrour, and Younes (2018) opined that the smart building concept uses smart technology to improve comfort and satisfaction and reduce energy consumption in a building. Moreover, Taktak, Abdennadher, and Rodriguez (2017) revealed that the smart building concept encompasses the development of the design, construction, materials stage, and the maintenance of the building life cycle. The aim is to reduce the cost of energy consumption, increase the occupant's comfort, and reduce harmful gases to human health and the environment.



Building Energy Management System based on Smart Grid (Source: https://www.semanticscholar.org/)

Various smart building and control concepts has been considered to enable flexible and sustainable operations. Research and technology development efforts in the energy and environmental system for buildings has rapidly evolved, each supporting the notion of smart applications can help to decrease energy waste to a minimum. However, rural and urban regions are different in terms of energy use per square meter and population. It is predicted that our future life will be influenced by the smart homes because they will provide services according to our preferences and will act intelligently. In recent times new buildings are planned and built according to new sustainability guidelines. Domestic homes are becoming even more energy efficient throughout the last periods, especially for two reasons, to reduce operational costs over the home cycle and to contribute to the environmental saving. Equally, the smart building market has seen significant growth in recent years, driven by advancements in IoT technology, data analytics, and artificial intelligence. According to a report by MarketsandMarkets (2020), the global smart building market size is expected to grow from USD 66.3 billion in 2020 to USD 108.9 billion by 2025, at a Compound Annual Growth Rate (CAGR) of 10.5%. This growth is fuelled by increasing awareness of energy efficiency, government initiatives promoting green buildings, and the need for more sustainable urban development. Currently smart building technologies offer a wide range of capabilities, including such as advance systems that can optimize energy usage by adjusting HVAC and lighting based on occupancy and external conditions, AI-powered analytics that predict equipment failures before they occur, reducing downtime and maintenance costs and sustenance of indoor air quality, security and access control.

Artificial Intelligence in Smart Buildings

According to luger (2008) AI may be defined as the branch of computer science that is concerned with the automation of intelligent behaviour. From this definition, AI is a discipline of computer science and it is based on a theoretical framework that covers this field. Such a definition highlights and expresses the lack of knowledge that characterises this field. Thus, AI researchers often build particular intelligent artefacts that are able to solve one isolated problem. For example, the Bayesian networks are often used to visualize patterns and the Markov models are often used to recognize speech. Thus, Pole et al. (2010) claim that AI is the field that studies the synthesis and analysis of computational agents that act intelligently (Pole & Mackworth, 2010). These definitions cover the term agents, which they define as something that acts intelligently in an environment. A refined definition of this term is a computational agent that makes decisions which can be expressed in computational terms. These decisions can be broken into small primitive operations that are implementable on physical devices. Describing an agent from a different angle provides clearness about its concept. An agent acts in environments where it is possible to use history and knowledge from prior observations. This means that an agent is able to learn from the past and make use of this learning to predict similar learned situations in the future.

Analysing agents from a more general perspective reveals that agent designers concerns about: modularity, modelling the world, uncertainty in actions, goals of preference, how to learn, and how to limit computational resources. In addition, this discussed agent-based concept is in close agreement with the definition attempt provided by Russell et al. (2009). Hence, by using a simple description it can be stated that artificial Intelligence (AI) is the intelligence of machines or software. This description covers elements such as knowledge management as well as reasoning and learning models; and it includes methods such as mathematical optimization, logic and probability. These AI definitions are useful in smart homes where elements to be predicted are of singular as well as complex nature. Singular systems rely on local simple event based intelligent artefacts to make decisions such as turning on the coffee-brewer. Complex systems need to use the past event-based history together with the present events to predict complex actions such as when the user goes to sleep. However, the challenge is to map these general definitions into usable ones that are optimal for smart home context, that are standardized and that are implementable with the available technology (Alam et al., 2012).

Application Areas of Artificial Intelligence in Smart Building

The application area for AI in smart buildings covers a wide range of applications such as control, automation and pattern recognition (learning). As Artificial Intelligence (AI) continuously revolutionize smart building systems by enabling more sophisticated, efficient, and responsive operations. AI technologies, particularly machine learning and adaptive control systems, are enhancing building performance, reducing energy consumption, and improving occupant comfort. These advanced algorithms process vast amounts of data from various building systems and sensors, learning from patterns and making intelligent decisions in real-time (Arditi et al., 2019). Under this section explores three key applications of AI in smart buildings: machine learning algorithms for building optimization, predictive maintenance, and adaptive control systems.

Machine Learning Algorithms for Building Optimization

Machine learning algorithms play a crucial role in optimizing various aspects of smart building operations. These algorithms can analyze historical and real-time data from multiple sources, including energy consumption patterns, occupancy levels, weather conditions, and user preferences, to make informed decisions about resource allocation and system adjustments. For instance, reinforcement learning algorithms have been successfully employed to optimize HVAC systems, resulting in significant energy savings without compromising occupant comfort (Wang & Hong, 2020). Neural networks and deep learning techniques have also been applied to predict building energy consumption with high accuracy, enabling more effective energy management strategies (Ahmad et al., 2018). By continuously learning from new data and adapting to changing conditions, these algorithms can fine-tune building systems to achieve optimal performance and energy efficiency.

Predictive Maintenance

Predictive maintenance is another area where AI is making significant contributions to smart building management. Traditional maintenance approaches often rely on fixed schedules or reactive responses to equipment failures, leading to unnecessary downtime and increased costs. AI-driven predictive maintenance uses machine learning algorithms to analyze sensor data from building equipment and systems, identifying patterns and anomalies that may indicate potential issues before they escalate into major problems (Carvalho et al., 2019). For example, vibration analysis and acoustic emission techniques, combined with machine learning, can predict failures in HVAC systems, elevators, and other critical building components (Tanga et al., 2020). This proactive approach not only reduces maintenance costs but also extends equipment lifespan, improves system reliability, and minimizes disruptions and discomfort of building occupants.

Adaptive Control Systems

Adaptive control systems represent the cutting edge of AI applications in smart buildings. These systems use advanced algorithms to continuously adjust building operations based on real-time data and changing conditions. Unlike traditional rule-based control systems, adaptive control systems can learn from their environment and modify their behavior accordingly. For instance, model predictive control (MPC) algorithms have been successfully implemented in smart buildings to optimize heating and cooling systems, adapting to weather forecasts, occupancy patterns, and energy prices in real-time (Serale et al., 2018). Similarly, adaptive lighting control systems can adjust illumination levels based on natural light availability, occupancy, and individual user preferences, significantly reducing energy consumption while enhancing visual comfort (de Bakker et al., 2017). These adaptive systems not only improve energy efficiency but also create more responsive and personalized environments for building occupants.

Internet of Things in Smart Buildings

The Internet of Things (IoT) has emerged as a disruptive technology in the development of smart buildings, enabling unprecedented levels of connectivity, data collection, and control. IoT in smart buildings refers to a network of interconnected devices, sensors and actuators that collect and exchange data over a communication network to optimize building performance, enhance energy efficiency, and improve occupant comfort (Minerva et al., 2015). We explore some key aspects of IoT implementation in smart buildings which include sensor networks and data collection, real-time monitoring and control, and integration with building management systems.

Profiling and Sensor Networks

At the heart of IoT implementation in smart buildings are extensive sensor networks that serves as a point of data collection for profiling throughout the building. These sensors measure various parameters such as temperature, humidity, occupancy, light levels, air quality, and energy consumption. Advanced sensor technologies, including wireless sensor networks (WSNs) and micro-electromechanical systems (MEMS), have made it possible to deploy large numbers of sensors cost-effectively and with minimal disruption to existing building infrastructure (Habibi et al., 2019). For instance, occupancy sensors using passive infrared (PIR) or ultrasonic technologies can detect the presence and movement of people in different spaces, enabling more efficient use of lighting and HVAC systems. Similarly, environmental sensors can monitor indoor air quality parameters such as CO2 levels, volatile organic compounds (VOCs) and particulate matter, ensuring a healthy and productive environment for occupants (Kumar et al., 2016). The data collected by these sensor networks forms the basis for profiling of buildings and occupants and also for intelligent decision-making and automated control of smart buildings.

Real-time Monitoring and Evaluation

Internet of Things (IoT) allows for real-time monitoring and control of various building systems, enabling immediate responses to changing conditions and user needs. This capability is crucial for optimizing energy consumption, maintaining comfort levels, and ensuring operational efficiency. Real-time data from IoT sensors can be used to adjust lighting levels based on natural light availability and occupancy, modulate HVAC systems according to current thermal conditions and occupant preferences, and manage power distribution to reduce peak demand (Minoli et al., 2017). Smart lighting systems can automatically dim or brighten lights based on occupancy and daylight levels, while smart thermostats can adjust temperature settings in response to occupancy patterns and weather forecasts. Moreover, IoT-enabled real-time monitoring facilitates rapid detection and response to anomalies or faults in building systems, enhancing safety and reducing downtime (Plageras et al., 2018). The ability to monitor and evaluate the building systems in real-time not only improves operational efficiency but also provides valuable insights for long-term planning and optimization.

Building Management Systems Integration Practice

The true extent of the impact of IoT in smart buildings is realized through its integration with building management systems (BMS). This integration creates a comprehensive platform for managing all aspects of building operations, from energy consumption to security and maintenance. IoT devices and sensors provide the BMS with a continuous stream of real-time data, enabling more informed decision-making and automated control. Advanced BMS platforms use this data to implement sophisticated control algorithms, optimize resource allocation, and provide intuitive dashboards for facility managers (Fierro & Culler, 2015). The Construction Specification Institute (2004) stipulated that integration of building automation systems should follow an acceptable pattern in the built industry. Thus, Bhusari et al (2015) highlights the following as the basic practice of building management integration: definition of scope, specification development, implementation and planning for future development. An integrated IoT-BMS system can coordinate between HVAC, lighting, and shading systems to optimize energy usage while maintaining occupant comfort. It can also facilitate predictive maintenance by analyzing equipment performance data and scheduling interventions before failures occur. Furthermore, the integration of IoT with BMS enables better interoperability between different building systems and allows for the implementation of more complex, building-wide optimization strategies (Arya et al., 2021). This holistic approach to building management not only improves operational efficiency but also enhances the overall performance and sustainability of smart buildings.

Impact of AI and IoT on Occupant Experience of Smart Building

The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in smart buildings holds immense potentials in significantly shaping occupant experience. Through real-time data collection, advanced analytics, and automated control systems, these technologies enable a more personalized and comfortable environment for building occupants. AI and IoT enhances occupant experiences through:

Personalized Comfort Settings: AI and IoT technologies are enabling unprecedented levels of personalization in building environments, allowing occupants to tailor their immediate surroundings to their individual preferences. Smart building systems can learn and adapt to individual occupant preferences for temperature, lighting, and other environmental factors through machine learning algorithms and data collected from IoT sensors (Park et al., 2019). For example, smart thermostats can learn occupants' preferred temperatures and adjust HVAC settings accordingly, while intelligent lighting systems can adapt to individual visual comfort needs based on task requirements and natural light availability. Some advanced systems even use wearable devices or smartphone apps to track occupant location and automatically adjust nearby environmental conditions (Ghahramani et al., 2018). This level of personalization not only enhances comfort but also contributes to increased productivity and overall satisfaction with the building environment.

Indoor Air Quality Management: Maintaining optimal indoor air quality (IAQ) is crucial for occupant health, comfort, and productivity. AI and IoT technologies are transforming IAQ management by enabling real-time monitoring and intelligent control of various air quality parameters. IoT sensors can be deployed to continuously measure factors such as CO2 levels, particulate matter, volatile organic compounds (VOCs), temperature, and humidity level (Moreno-Rangel et al., 2018). AI algorithms is applied in then applied in analysing this data to identify patterns, predict air quality trends, and automatically adjust ventilation systems to maintain optimal conditions. Machine learning models can predict CO2 buildup in rooms based on occupancy patterns and proactively increase ventilation rates to prevent discomfort and cognitive impairment associated with high CO2 levels (Pantazaras et al., 2018). Furthermore, AI-powered systems can integrate data from weather forecasts and outdoor air quality data to optimize the balance between natural and mechanical ventilation, ensuring a healthy indoor environment while minimizing energy consumption.

Space Utilization Optimization: As AI and IoT technologies continue to impact on the experience of occupant in smart building another area of impact is how building spaces are been utilized, leading to more efficient use of resources and improved occupant experiences. Occupancy sensors and advanced analytics help provide real-time insights into how different areas of a building are being used, allowing for dynamic space allocation and management (Labeodan et al., 2015). For example, in office environments, AI algorithms can analyze historical occupancy data and current trends to predict future space needs, enabling more effective hot-desking systems and meeting room allocations. In public spaces, foot traffic analysis powered by computer vision and AI can help optimize layout designs and improve visitor flow (Jiang et al., 2019). Moreover, these technologies help enhance safety and comfort by managing occupancy levels in shared spaces,

User Interfaces and Mobile Applications: The advancement of AI and IoT has led to the development of more intuitive and user-friendly interfaces for building occupants to interact with their environment. Smart building apps and dashboards, powered by AI, provide occupants with easy access to building controls and personalized information (Arditi et al., 2019). These interfaces often feature natural language processing capabilities, allowing users to control their environment through voice commands and other prompt tools. Mobile applications enable occupants to adjust their personal comfort settings, report maintenance issues, or navigate large buildings using indoor positioning systems. AI algorithms help analyze user interaction data to continuously improve the user experience and provide more relevant information and options. A smart building app might leverage data from user's routine and proactively suggest optimal times for tasks like booking a workspace or adjusting lighting preferences (Zou et al., 2018).

Implications of AI and IoT on Energy Efficiency of Smart Building Systems

One of the benefits of AI and IoT convergence in smart building is energy optimization. Traditional buildings often suffer from inefficiency due to static systems that operate without considering real-time conditions. In today's era of climate change and sustainability, the intersection of AI and energy has never been more important. The integration of this technology with Internet of Things has resulted in significant advancements in smart building management systems. As we move towards more sustainable energy sources and seek to improve energy efficiency, AI is playing a crucial role in making this transition possible. Its ability to analyse vast amount of data and provide insight and predictions is enabling AI algorithm to optimize energy usage, reduce waste and increase the use of renewable energy sources (Metallidou et al, 2020). IoT devices ranging from sensors to actuators are deployed throughout the infrastructure to gather real-time data on energy usage, occupancy patterns and temperature fluctuations. This flow of data serves as the basis for intelligent decision making enabled by AI algorithms. Adoption of AI and IoT in management of smart building system means that buildings can dynamically adapt based on data insight. AI algorithms can analyse historical energy consumption patterns, weather forecasts and occupancy data to adjust HVAC systems for optimal energy usage. Also, AI can predict energy demand spikes and proactively manage energy loads to prevent downtime. By intelligently distributing energy usage across different systems and timeframes and facilities, as a result reducing overall energy consumption and lower utility cost and minimizing environmental impact.

Adoption Challenges of AI and IoT in Smart Building Systems

While the integration of AI and IoT technologies in smart buildings offers numerous benefits, it also presents along with it several challenges and important considerations. As these technologies become more prevalent, stakeholders must address these issues. Addressing these challenges is crucial for the successful implementation and long-term sustainability of smart building solutions:

Data privacy and security concerns: The extensive data collection and processing inherent in AI and IoT systems raise significant privacy and security concerns. Smart buildings generate vast amounts of data, including sensitive information about occupant behavior, preferences, and movements. Ensuring the protection of this data from unauthorized access, breaches, and misuse is paramount (Geneiatakis et al., 2017). Cybersecurity threats to smart building systems can have severe consequences, potentially compromising not only occupant privacy but also building operations and safety. Implementing robust encryption protocols, secure authentication mechanisms, and regular security audits are essential steps in mitigating these risks. Additionally, compliance with data protection regulations such as the General Data Protection

Regulation (GDPR) in Europe or the California Consumer Privacy Act (CCPA) in the United States is crucial (Souri et al., 2020). Building owners and operators must also establish clear data governance policies, including data retention periods, access controls, and transparency about data collection and usage. As smart building technologies evolve, ongoing vigilance and adaptation of security measures will be necessary to address emerging threats and maintain occupant trust.

Interoperability and standardization issues; One of the significant challenges in implementing AI and IoT technologies in smart buildings is ensuring interoperability between various systems and devices from different manufacturers. The lack of universal standards and protocols can lead to fragmented systems, data silos, and reduced overall efficiency (Pasini et al., 2017). Interoperability issues can hinder the seamless integration of new technologies with existing building management systems, limiting the potential benefits of smart building solutions. To address this challenge, industry stakeholders are working towards developing common standards and protocols. Initiatives such as Project Haystack and the Brick Schema aim to create standardized semantic models for building data, facilitating better interoperability and data exchange (Balaji et al., 2018). Additionally, open protocols like BACnet, Modbus, and LonWorks are being increasingly adopted to enable communication between different building systems. However, achieving full interoperability remains an ongoing challenge that requires collaboration between technology providers, building owners, and industry organizations to establish and adopt common standards.

Initial implementation costs: The upfront costs associated with implementing AI and IoT technologies in smart buildings can be substantial, presenting a significant barrier to adoption, especially for existing buildings. These costs include hardware (sensors, actuators, gateways), software systems, network infrastructure, and integration with existing building management systems. Additionally, there may be costs related to staff training and potential disruptions during installation (Khaddaj et al., 2019). While the long-term benefits of energy savings, improved efficiency, and enhanced occupant experience can offset these initial investments, the payback period may be longer than traditional building upgrades. This can make it challenging to justify the investment, particularly for smaller organizations or in markets with lower energy costs. To address this challenge, some companies are exploring alternative financing models, such as Energy-as-a-Service (EaaS) or performance contracting, which can help distribute costs over time and tie payments to realized savings (Ioannou et al., 2020). Additionally, phased implementation approaches and careful cost-benefit analysis can help organizations manage the financial impact of smart building upgrades.

User adoption and training: The success of AI and IoT implementations in smart buildings heavily depends on user adoption and proper training of both occupants and facility management staff. Even the most advanced technologies can fail to deliver their intended benefits if users do not understand how to interact with them effectively or if they resist changes to established routines (Caird & Lane, 2015). Occupants may struggle with new interfaces or feel overwhelmed by the amount of control and information available to them. Facility managers and maintenance staff may require extensive training to operate and maintain new smart systems effectively. To address these challenges, it's crucial to involve end-users in the design and implementation process, ensuring that new systems are intuitive and aligned with user needs and preferences. Comprehensive training programs, user-friendly interfaces, and ongoing support are essential for successful adoption. Additionally, change management strategies should be employed to address potential resistance and facilitate a smooth transition to new smart building technologies (Day et al., 2020). Effective communication about the benefits of these systems, both in terms of personal comfort and broader sustainability goals, can help increase user acceptance and engagement.

Conclusion

The integration of AI and IoT technologies in smart buildings represents a significant leap forward in building management, energy efficiency, and occupant comfort. As we have explored throughout this paper, these technologies offer immense potential to transform the built environment, contributing to more sustainable, efficient, and user-centric spaces. This conclusion summarizes the key benefits of AI and IoT integration in smart buildings, highlights their importance for sustainable urban development, and emphasizes the need for continued research and development in this rapidly evolving field.

The integration of AI and IoT in smart buildings offers a plethora of benefits that significantly enhance building performance and occupant experience. This not only reduces operational costs but also minimizes the environmental impact of buildings. Enhanced occupant comfort and productivity are achieved through personalized environmental controls and automated adjustments that respond to individual preferences and occupancy patterns. Predictive maintenance capabilities enabled by AI and IoT reduce downtime and extend the lifespan of building systems, leading to significant cost savings over time. Moreover, these technologies improve building security through advanced access control and surveillance systems. The integration of AI and IoT also facilitates better space utilization and resource management, allowing building managers to make data-driven decisions about space allocation and usage. Collectively, these benefits contribute to creating more efficient, comfortable, and sustainable built environments that adapt to the needs of their occupants while minimizing resource consumption.

Implications of the Study

As AI and IoT technologies continue to evolve, the future of smart buildings holds exciting possibilities for enhanced efficiency, sustainability, and user experience. Emerging trends such as edge computing, advancements in AI algorithms and IoT devices, and wider adoption across various building types are set to transform the built environment. Edge computing is poised to play a crucial role in the future of smart buildings by enabling faster, more efficient processing of data closer to its source. By moving computational power to the "edge" of the network, near the sensors and devices generating data, edge computing can significantly reduce latency and enable real-time decision making (Shi et al., 2016). Edge computing can also help address privacy concerns by processing sensitive data locally, reducing the need to transmit all information to central servers or cloud platforms. The future of smart buildings is closely tied to the evolution of smart grids and the increasing adoption of renewable energy systems. As power grids become more decentralized and dynamic, smart buildings will play a crucial role in balancing energy supply and demand. Advanced building energy management systems (BEMS) will increasingly integrate with smart grid infrastructure, enabling buildings to participate in demand response programs and optimize energy consumption based on real-time pricing and grid conditions (Good et al., 2017). This integration will also facilitate the incorporation of on-site renewable energy generation, such as solar panels and small-scale wind turbines, allowing buildings to become active prosumers in the energy ecosystem.

The rapid pace of innovation in AI and IoT technologies promises to bring significant advancements to smart building capabilities. In the realm of AI, we can expect to see more sophisticated machine learning algorithms, including deep learning and reinforcement learning, being applied to building management challenges. These advanced AI models will be capable of handling more complex data sets, improving predictive maintenance, and optimizing building performance across multiple parameters simultaneously (Wang et al., 2020). While smart building technologies have primarily been associated with large commercial and office buildings, the future will likely see wider adoption across various building types. As costs decrease and solutions become more scalable, we can expect to see smart technologies increasingly implemented in residential buildings, schools, healthcare facilities, and retail spaces. In the residential sector, the growing popularity of smart home devices is paving the way for more comprehensive building automation systems in multi-family dwellings and single-family homes (Wilson et al., 2017).

References

Ahmad, T., Chen, H., Guo, Y., & Wang, J. (2018). A comprehensive overview on the data driven and large scale-based approaches for forecasting of building energy demand: A review. Energy and Buildings, 165, 301-320. https://doi.org/10.1016/j.enbuild.2018.01.017

Arditi, D., Mangano, G., & De Marco, A. (2019). Assessing the smartness of buildings. Facilities, 37(5/6), 269-285. https://doi.org/10.1108/F-03-2018-0041

Arya, A. K., Gupta, S., Mirza, A., & Sharma, R. (2021). Internet of Things (IoT) and its applications in smart building management. Materials Today: Proceedings, 46, 11581-11585. https://doi.org/10.1016/j.matpr.2021.02.612

Atzori, L., Iera, A., & Morabito, G. (2010). The Internet of Things: A survey. Computer Networks, 54(15), 2787-2805. https://doi.org/10.1016/j.comnet.2010.05.010

Balaji, B., Bhattacharya, A., Fierro, G., Gao, J., Gluck, J., Hong, D., ... & Whitehouse, K. (2018). Brick: Metadata schema for portable smart building applications. Applied Energy, 226, 1273-1292. https://doi.org/10.1016/j.apenergy.2018.02.091

Bhusari, S. V., & Watts, M. (2015) Affiliate Engineers Inc. retrieved from: https://www.csemag.com/articles/building/building-systems-integration-best-practices/

Caird, S., & Lane, A. (2015). Conceptualising the role of information and communication technologies in the energy management of householders: an evaluation of existing knowledges and future research directions. Energy Research & Social Science, 8, 32-44. https://doi.org/10.1016/j.erss.2015.04.005

Carvalho, T. P., Soares, F. A. A. M. N., Vita, R., Francisco, R. D. P., Basto, J. P., & Alcalá, S. G. S. (2019). A systematic literature review of machine learning methods applied to predictive maintenance. Computers & Industrial Engineering, 137, 106024. https://doi.org/10.1016/j.cie.2019.106024

Construction Specification Institute (2004) CSIMasterformat retrieved from: https://specsintact.ksc.nasa.gov/help/SIGeneral/CSIMasterformat.htm

Day, J. K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., ... & Pisello, A. L. (2020). A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort. Building and Environment, 178, 106920. https://doi.org/10.1016/j.buildenv.2020.106920 de Bakker, C., Aries, M., Kort, H., & Rosemann, A. (2017). Occupancy-based lighting control in open-plan office spaces: A state-of-the-art review. Building and Environment, 112, 308-321. https://doi.org/10.1016/j.buildenv.2016.11.042

Fierro, G., & Culler, D. E. (2015). Design and analysis of a framework for building management using BLE beacons. In Proceedings of the 2nd ACM International Conference on Embedded Systems for Energy-Efficient Built Environments (pp. 121-130). ACM. https://doi.org/10.1145/2821650.2821673

Geneiatakis, D., Kounelis, I., Neisse, R., Nai-Fovino, I., Steri, G., & Baldini, G. (2017). Security and privacy issues for an IoT based smart home. In 2017 40th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO) (pp. 1292-1297). IEEE. https://doi.org/10.23919/MIPRO.2017.7973622

Ghahramani, A., Tang, C., & Becerik-Gerber, B. (2018). An online learning approach for quantifying personalized thermal comfort via adaptive stochastic modeling. Building and Environment, 134, 186-197. https://doi.org/10.1016/j.buildenv.2018.02.029

Good, N., Ellis, K. A., & Mancarella, P. (2017). Review and classification of barriers and enablers of demand response in the smart grid. Renewable and Sustainable Energy Reviews, 72, 57-72. https://doi.org/10.1016/j.rser.2017.01.043

Haas, H., Yin, L., Wang, Y., & Chen, C. (2016). What is LiFi? Journal of Lightwave Technology, 34(6), 1533-1544. https://doi.org/10.1109/JLT.2015.2510021

Habibi, S., Safaei, F., & Mohamedali, M. (2019). Efficient distribution of sensor nodes in the Internet of Things networks. In 2019 IEEE 5th World Forum on Internet of Things (WF-IoT) (pp. 713-718). IEEE. https://doi.org/10.1109/WF-IoT.2019.8767185

Ioannou, A., Itard, L., & Agarwal, T. (2020). In-situ real time measurements of thermal comfort and comparison with the adaptive comfort theory in Dutch residential dwellings. Energy and Buildings, 215, 109873. https://doi.org/10.1016/j.enbuild.2020.109873

Javed, A., Heljanko, K., Buda, A., & Främling, K. (2020). CEFIoT: A fault-tolerant IoT architecture for edge and cloud. In 2020 IEEE 4th International Conference on Fog and Edge Computing (ICFEC) (pp. 42-49). IEEE. https://doi.org/10.1109/ICFEC50348.2020.00014

Jiang, S., Yao, W., Hong, J. E., & Liu, Y. (2019). Visualization-based spatial analysis of tourist movements using location-based social media data. ISPRS International Journal of Geo-Information, 8(9), 413. https://doi.org/10.3390/ijgi8090413

Khaddaj, M., Srour, I., & Ghaddar, N. (2019). A real-options based model for evaluating the financial performance of smart building energy retrofits. Energy and Buildings, 196, 206-216. https://doi.org/10.1016/j.enbuild.2019.05.029

Kumar, P., Skouloudis, A. N., Bell, M., Viana, M., Carotta, M. C., Biskos, G., & Morawska, L. (2016). Real-time sensors for indoor air monitoring and challenges ahead in deploying them to urban buildings. Science of The Total Environment, 560-561, 150-159. https://doi.org/10.1016/j.scitotenv.2016.04.032

Labeodan, T., Zeiler, W., Boxem, G., & Zhao, Y. (2015). Occupancy measurement in commercial office buildings for demand-driven control applications—A survey and detection system evaluation. Energy and Buildings, 93, 303-314. https://doi.org/10.1016/j.enbuild.2015.02.028

Li, S., Da Xu, L., & Zhao, S. (2019). 5G Internet of Things: A survey. Journal of Industrial Information Integration, 10, 1-9. https://doi.org/10.1016/j.jii.2018.01.005

Lim, C., Kim, K. J., & Maglio, P. P. (2021). Smart cities with big data: Reference models, challenges, and considerations. Cities, 101, 102712. https://doi.org/10.1016/j.cities.2020.102712

MarketsandMarkets. (2020). Smart Building Market by Component (Solution, Services), Solution (Security & Emergency Management, Energy Management), Services, Building Type (Residential, Commercial, Industrial), Region - Global Forecast to 2025. https://www.marketsandmarkets.com/Market-Reports/smart-building-market-1169.html

Minerva, R., Biru, A., & Rotondi, D. (2015). Towards a definition of the Internet of Things (IoT). IEEE Internet Initiative, 1, 1-86.

Minoli, D., Sohraby, K., & Occhiogrosso, B. (2017). IoT Considerations, Requirements, and Architectures for Smart Buildings—Energy Optimization and Next-Generation Building Management Systems. IEEE Internet of Things Journal, 4(1), 269-283. https://doi.org/10.1109/JIOT.2017.2647881

Moreno-Rangel, A., Sharpe, T., Musau, F., & McGill, G. (2018). Field evaluation of a low-cost indoor air quality monitor to quantify exposure to pollutants in residential environments. Journal of Sensors and Sensor Systems, 7(1), 373-388. https://doi.org/10.5194/jsss-7-373-2018

Pantazaras, A., Lee, S. E., Santamouris, M., & Yang, J. (2018). Predicting the CO2 levels in buildings using deterministic and identified models. Energy and Buildings, 165, 515-523. https://doi.org/10.1016/j.enbuild.2017.12.038

Park, J. Y., Ouf, M. M., Gunay, B., Peng, Y., O'Brien, W., Kjærgaard, M. B., & Nagy, Z. (2019). A critical review of field implementations of occupant-centric building controls. Building and Environment, 165, 106351. https://doi.org/10.1016/j.buildenv.2019.106351

Pasini, D., Ventura, S. M., Rinaldi, S., Bellagente, P., Flammini, A., & Ciribini, A. L. C. (2017). Exploiting Internet of Things and building information modeling framework for management of cognitive buildings. In 2017 IEEE International Smart Cities Conference (ISC2) (pp. 1-6). IEEE. https://doi.org/10.1109/ISC2.2017.8090790

Plageras, A. P., Psannis, K. E., Stergiou, C., Wang, H., & Gupta, B. B. (2018). Efficient IoT-based sensor BIG Data collection–processing and analysis in smart buildings. Future Generation Computer Systems, 82, 349-357. https://doi.org/10.1016/j.future.2017.09.082

Russell, S. J., & Norvig, P. (2020). Artificial intelligence: A modern approach (4th ed.). Pearson.

Serale, G., Fiorentini, M., Capozzoli, A., Bernardini, D., & Bemporad, A. (2018). Model Predictive Control (MPC) for enhancing building and HVAC system energy efficiency: Problem formulation, applications and opportunities. Energies, 11(3), 631. https://doi.org/10.3390/en11030631

Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. IEEE Internet of Things Journal, 3(5), 637-646. https://doi.org/10.1109/JIOT.2016.2579198

Souri, A., Hussien, A., Hoseyninezhad, M., & Norouzi, M. (2020). A systematic review of IoT communication strategies for an efficient smart environment. Transactions on Emerging Telecommunications Technologies, 31(10), e3736. https://doi.org/10.1002/ett.3736

Tanga, D., Gu, J., Chen, K., & Yu, S. (2020). Intelligent fault diagnosis of rolling bearings using deep wavelet auto-encoder with extreme learning machine. Knowledge-Based Systems, 188, 105004. https://doi.org/10.1016/j.knosys.2019.105004

Wang, Z., & Hong, T. (2020). Reinforcement learning for building controls: The opportunities and challenges. Applied Energy, 269, 115036. https://doi.org/10.1016/j.apenergy.2020.115036

Wilson, C., Hargreaves, T., & Hauxwell-Baldwin, R. (2017). Benefits and risks of smart home technologies. Energy Policy, 103, 72-83. https://doi.org/10.1016/j.enpol.2016.12.047

Zemtsov, S., Barinova, V., & Semenova, R. (2021). The risks of digitalization and the adaptation of regional labor markets in Russia. Foresight and STI Governance, 15(2), 21-33. https://doi.org/10.17323/2500-2597.2021.2.21.33

Zou, H., Zhou, Y., Yang, J., & Spanos, C. J. (2018). Device-free occupancy detection and crowd counting in smart buildings with WiFi-enabled IoT. Energy and Buildings, 174, 309-322. https://doi.org/10.1016/j.enbuild.2018.06.040