PENINSULA PUBLISHING LLC

KHWARIZMIA
Vol. (2025), 2025, pp. 11–22
ISSN: 3078-2694

Research Article

Smart Building Systems: A Confluence of Architecture and Technology

Omar G. Ahmed[1,*]

[1] Department of Electric Drive, Mechatronics and Electromechanics, South Ural State University, Chelyabinsk, 454080, Russia.

ARTICLE INFO

Article History
Received 5 Oct 2024
Revised: 25 Nov 2024
Accepted 26 Des 2024
Published 12 Jan 2025

Keywords
Green Architecture,
Urban Development,
Intelligent Buildings.

ABSTRACT

Architecture is constantly evolving as its relationship with technology grows. Smart building systems are the combination of the architectural and technological dimensions of a structure. These are networked architectures which rely on Internet of Things (IoT) devices, artificial intelligence (AI) and automation to optimize the operational performance, sustainability, and occupant experience of a building. This paper discusses the emergence and advancements of smart building systems, their characteristics and technological architecture, and their contribution to energy efficiency and sustainability. It also addresses the challenges of interoperability, cybersecurity, and user interface design in smart buildings, helping to understand the trends and developments of smart architecture and their impact on the future of urban centers. Moreover, case studies illustrate the innovative design and best practices of an intelligent building system or a set of networked buildings to transform the built environment with smart technologies.

1. INTRODUCTION

The past two decades have seen dependence on and integration of technology into daily life increase dramatically. From simple transformations such as households acquiring computers and internet connectivity, advances in technology then began to blend with everyday environments via personal devices like mobile phones or tablets. This evolution grew to a point where widely adopted technology became ‘smart,’ meaning buildings, streets, cities, and even objects from trash bins to coffee cups embedded technology so that they could sense and communicate information about their surroundings and interact with users. Technology has altered daily activities and environments, but it also significantly transformed how users interact with their commercial and residential buildings. Simply having sensors and control devices installed in the architecture does not mean a technological system is ‘smart.’ It can also mean multiple things simply by the choice of words: intelligent, automated, adaptive, responsive, benign, or even aware [1]. Regardless of the terminology complexity, the framing of ‘smart building systems’ is essential to establish a foundational understanding. Following that, it explores why these systems are often desired in newly constructed and existing buildings and clearly defines the scope of this discussion. In urban environments where buildings account for about 75% of electricity consumption, architectural focus has recently shifted from design aesthetics and characteristics that accommodate human activities to enhancing buildings’ operational efficiency. To this end, mechanical systems controlling heating, cooling, ventilation, air quality, and lighting are equipped with control devices that allow technology to automate their operations rather than rely on users manually adjusting settings [2]. However, automation alone does not ensure efficiency. Problems arise because all mechanical systems control functions based on preset schedules or static rules irrespective of occupancy.

2. DEFINITION AND SCOPE OF SMART BUILDING SYSTEMS

In recent decades, the term "smart buildings" (and its synonyms: intelligent, automated, or high-tech buildings) has emerged as a new descriptor for selected architectural works. To begin the discussion, it is essential to clarify what is specifically meant by the term "smart buildings." The focus is on artificially intelligent and autonomic smart buildings, which are buildings where the architectural and technological systems converge to create a coherent complex of autonomous intelligent systems. Buildings can be considered "smart" when the following criteria are satisfied: (i) the basic building systems have a significant degree of automation and/or artificial intelligence, (ii) the building systems are networked and have a significant degree of connectivity, and (iii) the smart systems are designed to be as user-centric as possible [1].
The convergence of architecture and technology is an essential aspect of smart building systems. An architectural system can be defined as designed and constructed entities that have a predetermined function. A building is a physical architectural system, and its constituent technological systems are non-physical architectural systems designed and implemented to

*Corresponding author email: omrgml@outlook.com
DOI: https://doi.org/10.70470/KHWARIZMIA/2025/002

enhance the performance of the physical architectural system. A smart building system is an artificially intelligent architectural system that integrates physical architectural smart systems and their non-physical technological smart systems to create a coherent ensemble that utilizes artificial intelligence to adapt and optimize its performance in a given environment. Systems typically found in smart buildings – HVAC, lighting, security, AV, fire safety, and other systems – can be considered smart building systems when either one or both of the following criteria are satisfied: (i) a system is networked or has a significant degree of connectivity, and/or (ii) a system has a significant degree of automation and/or artificial intelligence. Because of this convergence, the scope of smart building systems is deliberately defined broadly to include all system types typically encountered in buildings [2].

Due to their complexity and the generally emerging state of the technology, smart building systems should ideally be designed and implemented by multi-disciplinary teams that include (at least) architects, engineers, computer scientists, and IT personnel. The goal is to cooperate in the design and implementation of the smart systems from initial architectural and technological design through the choice of technology and products to final integration and testing [2]. For practical reasons, it is more common for the design and implementation of smart building systems to be split between distinct disciplines – generally, one or two companies are responsible for the architectural and technological design, and a different company is responsible for the implementation. Even though it is common for smart systems to be designed by separate architectural and technological design teams, it is essential to understand that smart building systems have a coherent complex of architectural and technological smart systems at their core. Understanding this complexity helps to avoid misinterpretations of the versatility of smart building systems, which can create problems when discussing the state-of-the-art technology and debating alternative solutions [3].

2.1 Evolution of Building Automation Systems

The initial influx of mechanical controls in buildings began with the steam and hydronic systems, where control was necessary to maintain comfort conditions. Many such systems were installed up to the 1940s, and it became evident that some level of control was necessary in buildings for energy conservation as well as human comfort [1]. Most control systems began with manual control, where a human operator monitors building systems and makes adjustments as necessary. Various gauges and indicators were collected in one central location, usually referred to as the control room where the human operators stood in front of a large panel of control devices [4].

As the building systems being controlled became more complex, it was evident that this manual system could not keep up with the demand. For instance, the 1930s city's most elaborate control system was designed by the New York City's Municipal Broadcasting System, mostly under the direction of a single engineer who chained-moved from building to building. The first automatic control was implemented and aimed at maintaining comfort conditions in opera houses. Several control systems were implemented at the city's control buildings, and eventually, a central station was built to house the many controls put in place with levers, gears, and pulleys. The automated technologies mostly mimicked the manual controls, and other examples of early automated systems include pneumatic controls. In buildings, these technologies were employed initially to control dampers for ventilation, followed by temperature control. The primary advantage of these systems was that they did not require electricity. By the early 1960s, the invention of electronics-based systems, updated pneumatic control systems, and local control loops were used to maintain desired conditions [5].

Trends in and methodologies for the integration of various systems found in buildings have been developed and executed with varying degrees of success. Force integration refers to the situation where a single manufacturer produces all devices and controllers. In passive integration, controllers manufactured by various companies can accept some common signals. The coordinated building control requires special controllers to be added to the system, where integrated systems can communicate through a central computer. By the 1980s, it became apparent that the demands on building systems were changing and that a more sophisticated approach was needed to ensure the efficiency of newly built systems. The 1980s energy crises and subsequent increases in energy prices motivated building owners to demand more efficient buildings. The demand for convenience to the users of buildings also increased during this decade. As offices were equipped with increased amenities, the buildings grew more complex, and keeping up with the demands became increasingly burdensome [6].

3. ARCHITECTURAL CONSIDERATIONS

As technology becomes integrated within the realm of architecture, certain contemplations arise that must be addressed within the architectural design process. It is believed that architects, who hire and oversee the execution of the technologies within their designs, are responsible for the coherence of these designs: an obligation to ensure that the integration of technology does not overshadow or compromise the architectural qualities of the design but instead enhances them [7]. However, as an ever-increasing amount of building systems and components become "smart," there is a necessity for architects to work closely with experts of the technology in order to execute the designs properly. Therefore, consideration must be given to how built environments can be designed to accommodate and enhance smart technologies. As smart technologies become widely implemented within buildings, a new approach to architecture is necessary; an approach that considers how the technology will affect the building on a holistic level throughout the design process. By addressing recent architectural technology implementations, considerations are illuminated that will serve as a basis for future architectural designs involving smart systems. Through an examination and exploration of recently completed architectural designs that implement smart technologies, the conjoining of architecture and technology is highlighted, while also addressing how these designs are possessing unique qualities that are necessary to consider in future designs. After a brief introduction to the current state of smart technologies in buildings and an overview of the necessary architectural considerations, three specific architectural qualities are highlighted. The first quality emphasizes that smart technologies are most effective when designed to be invisible, enhancing the building without being seen. The second quality discusses a design approach that smart technologies should be considered and designed for on a building-wide scale, focusing on how a technology can determine a design's geometry and space distribution. The third quality demonstrates that structures incorporating smart technologies should possess a high level of autonomy, allowing the systems to control themselves without outside intervention. These qualities are ultimately the result of a careful consideration of the aforementioned architectural approaches and challenges [8].

3.1 Integration of Technology in Architectural Design

The initial part of the discussion closely examines how technology integrates into architectural design. The definition of architecture contextually includes the spatial and material organization of the built environment, whether it be new or retrofitted structures. Technology refers to information and communication technology that can be embedded in, or interact with structures to enhance their responsiveness, functionality, ecological performance, and the comfort of their users. Several technologies are outlined that can enhance the load-bearing structures' functionality or responsiveness to environmental aspects and climate control enhance user comfort [9]. These include localized or large-area microclimatic control concepts, building-integrated photovoltaics, artificial intelligence in climate control, technology-integrated spaces for interaction with nature, technology-integrated spaces for interaction between users, technology-integrated spaces for interaction between users and outside, and technology-integrated monitoring of structural health.

Some key aspects must be considered when determining how technology should be situated within the design. First, different technologies may imply different spatial organization. Some technologies may cluster the spaces or create them as a string, while some may create the need for large or small spaces, closed or open spaces, and public or private spaces. Second, how technology is situated within the design affects the aesthetic implications. The way technology sensitivity and style affect the structural materiality, detailing, and design approach also influence the aesthetic interpretation of the design. If the technology is sensitive to environmental aspects, it typically affects the detailing, materiality, and design approach of the components in the building envelope that ensure the appropriate performance of the technology. If the technology is sensitive to the structural health, a technology implementation may also require additional components that may influence the materiality and detailing of the structure. Like the enclosures, the additional components may imply new design motives and thus affect the aesthetics of the construction [10].

In the context of new designs, smart technologies are often considered after the design is completed. This approach can be considered catastrophically wrong regarding the active technologies in the new design because it is extremely difficult to find the appropriate design solution that harmoniously integrates architecture and technology. The approach also carries over challenges when retrofitting the existing buildings with smart technologies. With this, design solutions generally create unintegrated add-ons, leaving the existing areas that require intervention due to the design principles of the smart technologies instead of presenting new states that creatively integrate the architecture/design and smart technologies. Nevertheless, some innovative design approaches blend architecture/design and smart technologies harmoniously. Bioclimatic and digital design strategies are considered fundamental for establishing a creative synergy between smart technologies and design solutions for new smart constructions .

To achieve the new objectives of smart buildings, an interdisciplinary design approach involving architects/designers and computer engineers is necessary. The integration of smart technologies should be considered and addressed from the very beginning of the design process. Otherwise, there is a danger that the design solutions will address the architectural aspects or technology aspects separately; thus, a creative synergy will not be achieved. With this examination, the methodologies that address and determine how technologies integrate the architectural design from the early phases are presented. One objective is to provide a basis for methodology that aims to enhance the constructive performance regarding the integration of smart technologies within the architecture/design. The second objective is to present consideration methodologies for aspects that significantly influence the design approach and desired outcomes and to highlight the importance of consideration from the onset within the design processes.

Further, the design and state considerations of monitoring technologies for structural health are outlined. In this regard, design flexibility and adaptivity of the construction or design over time due to the technology consideration are explained. Generally, the design could be either largely fixed or indefinite in regard to anticipated flexibility and adaptability; the consideration of this aspect alters the experimental parameters of the design. It is concluded that technologies effecting fixed design states impose stricter rules on the thought process and design and restrict potential flexibility in the design if the monitoring technologies were not already considered at the ontogeny stage. Ultimately, the necessity to consider [11].

4. TECHNOLOGICAL FOUNDATIONS

A smart building system is a comprehensive system powered by an interconnected network of various technologies that facilitate building management and monitoring. In general terms, smart building systems rely upon a set of interconnected technologies that ensure building connectivity, automation, and data management . The current buildings or systems are continuously altered by the evolving and improving technologies used to design and construct buildings. A basic understanding of the underlying technologies is imperative to comprehend building systems thoroughly [12].

The Internet of Things (IoT), comprising a network of interconnected objects, is the most fundamental and critical technology for smart environments. IoTs can collect and manage data in real-time across every system within a building, including mechanical, electrical, and plumbing (MEP) systems, life safety systems, information technology (IT) systems, and architectural systems [4]. Internet-enabled sensors embedded within a building system can gather data on system performance and occupant interaction to identify system inefficiencies or faults. This data can then be transmitted to other systems for analysis and aggregation. IoT devices and technologies can augment a building's functionality beyond the capability of solely designed systems and can passively observe and learn data from the environment [13].

Cloud computing architectures are also imperative for smart building systems. Sufficient data storage is required to collect all building-generated data. These building data can also aid in enhancing system, component, or building efficiency through post-processing and machine learning applications. Currently, building data is typically stored in cloud servers owned by large firms who also offer post-processing services alongside the cloud. Artificial intelligence (AI) is another foundational technology for smart building systems. AI algorithms can enhance the efficiency of systems, components, or controls and generate actionable insights based on the data collected and stored in building systems.

The building sector plays a significant role in energy consumption and greenhouse gas (GHG) emissions worldwide. The advancement and improvement of technology used to construct and operate buildings affect the performance of buildings. Evolving technologies can be strategically harnessed to actively influence the design and operation of buildings in the future. Generally, technology development implies improvement, but new advancements complicate future building designs, as both good and bad technologies (or side effects) converge in building solutions. Understanding the convergence of technologies and their implications for future buildings is vital to minimizing adverse effects while maximizing holistic benefits [14].

4.1 Internet of Things (IoT)

The discussion now turns to one of the smart/building systems technologies in more detail. Within this discussion, individual systems technologies will be reviewed, including a description of how they work, how they are being used in buildings, and examples of applications. This subsection focuses specifically on the Internet of Things (IoT). A smart building refers to a structure that uses advanced monitoring and control systems to improve the efficiency of its operations. It can involve the installation of new systems or the integration of existing ones, each with a unique architecture typically based on a combination of hardware, software, and data management capabilities. In essence, buildings become "smart" when they are equipped with systems capable of making decisions based on data from the environment to control elements such as heating, ventilation, air conditioning (HVAC), lighting, energy usage, safety measures, and many more. These systems can connect various devices within a building to the Internet and provide capabilities for real-time monitoring and control . By integrating IoT technologies, building systems can share data and turn buildings into "smart" environments, changing how buildings are used and managed. IoT technologies can apply to various systems within buildings, including HVAC, lighting, energy consumption, occupancy detection, and access control, to name a few. Each application involves deploying different types of sensors, actuators, and devices designed to control or monitor a specific aspect of the building environment. For example, a traditional HVAC system without any smart features typically relies on a fixed schedule to increase or decrease heating/cooling based on time. By implementing occupancy sensors along with smart control technology, the HVAC system can monitor space occupancy in real-time and adjust its operation according to the actual usage of the space. Since most building systems already collect some form of operational data, the primary benefit of connecting them with IoT technologies is enhanced data analytics, enabling new insights into the building operations to improve operational efficiency. Implementing IoT technology in building systems typically involves several hardware and software components. Sensors deployed across the building collect data and send it to a cloud platform for processing. The cloud platform runs the data analytic algorithms that generate insights into the building operation. These insights are then sent to a management interface through which engineers can monitor the system and make necessary adjustments. Some applications also include data feedback loops that can automatically control the building systems based on the analysis results. Currently, various IoT applications exist for monitoring and controlling different systems in buildings. Most early-stage implementations focus on energy management systems that collect data related to energy consumption, occupancy patterns, and environmental measurements to detect inefficiencies in energy usage. There is a growing interest in developing new algorithms to take advantage of this data for enhanced analysis of energy usage in buildings. Research involving the implementation of an IoT light monitoring system in a smart building is also underway. The data collected from the IoT light sensors is quantitatively analyzed to evaluate the performance of the installed lighting systems in order to improve user comfort while saving energy. If widely adopted, IoT technology can significantly improve the energy management of buildings, making them more efficient and less harmful to the environment. In addition to energy and resource management, building systems often require monitoring to provide a safe and comfortable environment for users. IoT systems can also be implemented to monitor environmental factors such as temperature, air quality, and light intensity. Data from different environmental sensors can be analyzed to provide acoustic comfort, safety, and user comfort to building occupants. While IoT technologies offer various potential applications and benefits in building systems, each application involves multiple challenges that need to be addressed to successfully implement IoT technologies. Integrating a large number of IoT devices from various manufacturers into a single system is particularly challenging due to the wide range of wireless communication protocols and data formats used by different devices. It requires specialized systems that can act as network gateways to bridge the gap between devices that use different protocols. Moreover, as more devices and systems are interconnected, there is a growing concern regarding system security and privacy. Most IoT-enabled applications involve collecting potentially sensitive data that need to be adequately protected from unauthorized access and manipulation. Smart buildings often involve the integration of IoT technologies into pre-existing systems, which can make them more vulnerable to exploitation [15].

5. KEY COMPONENTS OF SMART BUILDING SYSTEMS

It is essential to identify the key components of smart building systems. Understanding what makes a building smart is a necessary first step to pondering how to make it so. A smart building is not merely a single intelligent system; instead, many systems work together to create a smart environment. These systems are often composed of components that perform a vital function in the building's operation or energy use. Components can be as simple as a single thermostat controlling a heating vent or as complex as an integrated multi-zoned HVAC, lighting, and building section control system. There are five key energy-related systems or "building elements" that make up the building's intelligence. These systems are HVAC, lighting, appliances, building enclosure, and renewable energy systems. HVAC systems monitor and control the temperature, humidity, and air quality of the building environment in relation to occupant comfort. Lighting systems control the intensity, spectral quality, and distribution of artificial lighting in a space, coordinating their operation with the input from occupancy and daylight sensing. Security systems monitor the occupancy and access of building spaces using mechanisms such as closed-circuit cameras, motion sensors, and door locks. Each of these systems can include a variety of devices, from simple on/off sensors to complex multi-input control units. Additionally, many of these systems include user-controlled components, such as thermostats, dimmers, and fans, through which the occupants can influence and control how the systems operate [16].

The basic building system as defined here consists of the necessary sensing and control components to create an intelligent environment. However, it is the integration of these components that make it "smart." For example, a simple lighting control system that turns lights on and off in a room as occupancy is detected is an intelligent system. However, a lighting control system integrated with a HVAC system that turns off the lighting when sufficient daylight is available is a smarter system. Regardless of the levels of intelligence or smartness, key components must be present for the operation of the building systems. Each of these components perform the basic functions of a building system; a control algorithm interprets the data from the sensors and determines the appropriate state of the actuators. In a simplest form, a system may consist of a single sensor and actuator pair, but often a single sensor input may control several actuators or multiple sensors will determine the state of a single actuator. Components are grouped into three types, with each type containing several representative examples. The first type is systems, each with a specific control objective in the building, such as HVAC, lighting and security systems. These are generally more complex control systems containing multiple sensors and actuators. The second type is a user interface, providing a means to interact with the smart building systems. User interfaces allow for the adjustment of control parameters, setting of operation schedules, and displaying information on system performance. The third type is a data collection and analysis system. Data collection can include both building system data and external data such as weather, utility pricing, or occupancy patterns. Similarly to the user interface component, data analysis can be used for adjusting control strategies and scheduling operation of the system. The final two component types are concerned with the monitoring of building system performance and the ability to alter component behaviour in response to system monitoring. All components must be designed to ensure they can change in scale and operate with multiple component implementations. Building systems may be designed in such a way that a new implementation of a component can be added with little alteration to the existing control algorithms. For example, it is possible to develop a new type of sensor that does not require any change to the control algorithm if the sensor operates in the same way as existing sensors in the system. Control component design should accommodate the ability for each component to change in scale. For example, a single design could be used for temperature sensors controlling HVAC equipment; however, this design could be implemented at many different locations throughout the building. Simple control strategies such as that described earlier can only be applied effectively to a component with a single implementation [17].

5.1 Sensors and Actuators

A smart building system comprises a set of devices, environmental sensors, and actuators designed to automate processes in a building or campus. Smart buildings utilize interconnected technologies to monitor and manage the building's operations intelligently. A set of well-defined modules, each responsible for controlling a specific smart building functionality, is designed. Every module comprises a collection of devices, environmental sensors, and actuators, simple local servers, and necessary embedded software. An actuator receives commands in the form of control signals and performs a physical action. An actuator can be considered the reverse of a sensor: a sensor transforms a physical quantity into a signal transmitted for observation and analysis, while an actuator transforms a signal into a physical quantity. The smart building system uses five different types of actuators: Variable Air Volume (VAV) Actuators, Dampers, Valves, Lights, and Fan Speed Controllers. A Sensor is defined as a device that detects events or changes in quantities and provides a corresponding output, generally as an electrical or optical signal. The output of a sensor usually requires processing to extract useful information about the detected change or event. Sensors are the starting point for data acquisition in smart building systems. A sensor measures a physical quantity, such as temperature, humidity, occupancy, or light intensity, to determine environmental conditions. The sensor transforms this measurement into a signal that is transmitted for observation and analysis. Often, the output signal from a sensor is converted into a digital form because digital data can be manipulated using computers [18]. A smart building system uses fourteen different types of sensors, including temperature, humidity, motion, CO_2, light, pressure, and air quality. The data from the smart building system can be analyzed and interpreted by computerized systems. The "smart" capability of a system refers to its ability to observe, analyze, and act upon the data collected by its sensors to optimize decision-making and control. When the data collected by the sensors are used to automate the operation of the system without requiring human intervention, the system is described as automatic. For example, a common smart building application is using temperature sensors to control and automate Heating, Ventilation, and Air Conditioning (HVAC) equipment. HVAC equipment can be turned on, turned off, or operated at different levels depending on the temperature measured by the sensors. The technical systems like , water, air quality, interfaces, sensors/actuators, lighting, security/privacy, and sound which will be further developed by experts, were accessed from the inside and/or outside and located in specific places designated by the technical team [19] as shown in Figure 1. Other smart building applications include automatically managing and controlling lighting, doors, window shades, and water systems. The accuracy and reliability of a smart building system's sensors are fundamental for the system to perform optimally. In particular, the accuracy of a sensor system depends on the type and quality of the individual sensors that comprise it. There are many types of sensors, with diverse operating principles and specifications in terms of factors such as sensitivity, bandwidth, linearity, resolution, and noise. Recent trends in sensor technologies include miniaturization, which allows integrating multiple sensors on a single microchip, and wireless sensor networks that eliminate the need for wired connections between sensors and control units. The networking capability of wireless sensors makes it possible to adopt flexible sensor placement strategies, and the miniaturization of sensors facilitates embedding sensing functionality within other equipment. For example, the need for delicate machinery such as optical mirrors is eliminated by micro-electromechanical system technology (MEMS), which allows the integration of tiny mirrors and sensors on a single chip. As an illustration of how smart building technology can be used to promote energy efficiency, Lighting Control Technological Innovations incorporate novel actuator designs that tilt light fixtures, leading to more focused light distribution, improved visual comfort for occupants, and reduced energy waste. Another example is the Air Quality Control Technological Innovation, where the zonal control of air-conditioning systems is integrated with occupancy sensors that detect the position of occupants in a room. Having air-conditioning ducts in the ceiling is conventional, forcing conditioned air to flow downward towards the occupants. Accordingly, the design of diffusers mounted on the ceiling is intended for a widespread air distribution. This technology innovation replaces ceiling ducts with ductless light fixtures that also blow air, actively directing the airflow towards seated occupants [20]

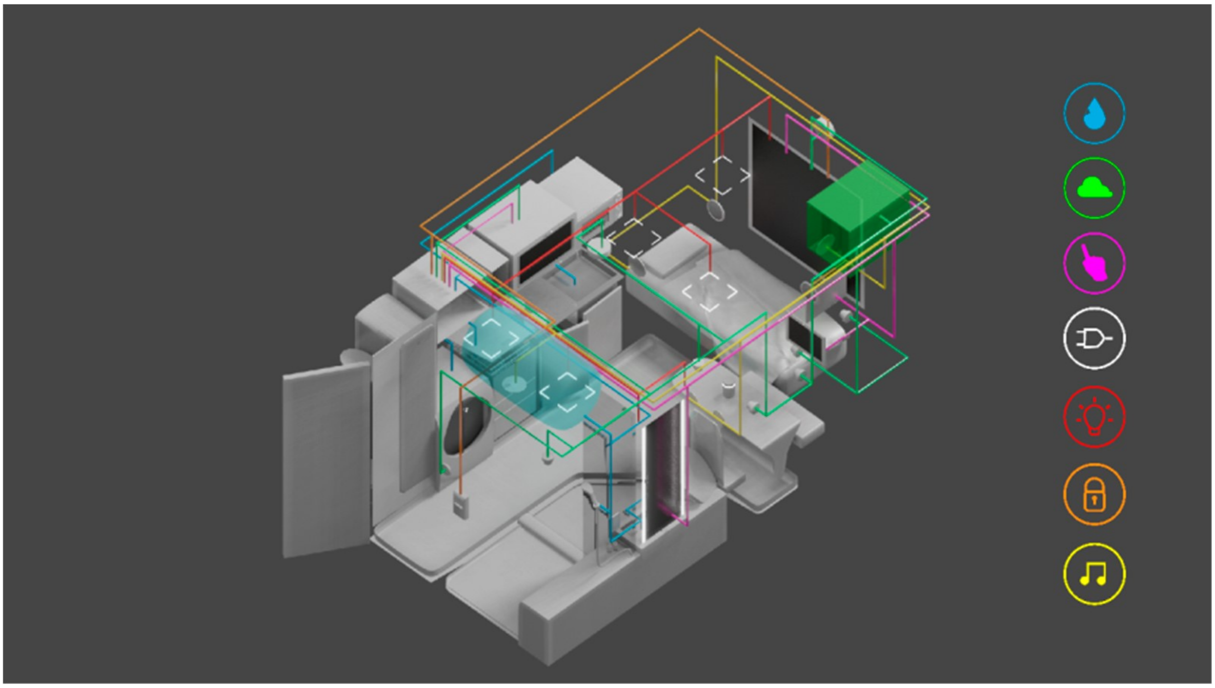

Fig 1. Technical systems scheme [20]

6. ENERGY EFFICIENCY AND SUSTAINABILITY

Buildings consume 41% of global energy, driving an essential focus towards energy efficiency and sustainability for new constructions and retrofitting existing structures to reduce energy waste. Smart building systems, embedding technology to monitor and control buildings, have emerged as a solution for energy efficiency and sustainability. Using intelligent systems, structures can actively reduce energy consumption and associated operational costs. Automated controls for lighting, shading, and HVAC systems based on detected occupancy levels and real-time adjustments can significantly lower energy waste compared to conventional systems [21].

Computers and sensors combined with building management systems (BMS) allow monitoring and automatic adjustments to building performance, impacting energy savings in commercial properties. The discussion on smart buildings focuses on currently available solutions to achieve energy efficiency and sustainability in contemporary architecture. The relationship between smart buildings and green building certifications is elaborated, explaining their criteria and highlighting best practices for sustainable design. Energy-efficient technologies in lighting, HVAC, and building envelope are illustrated with case studies. Each examined building implements various energy savings technologies, such as automated lighting and shading, demand-controlled HVAC, natural ventilation, and real-time energy monitoring.

While many structures incorporate some energy-saving technologies, the overarching challenge remains how to reduce excessive energy use. Although the initial investment costs for energy-efficient technologies are higher, financial savings from reduced energy expenses can return the investment in a few years. Moreover, many energy-efficient technologies require adjustments and tuning after installation, underscoring the importance of skilled personnel and policy in saving energy. Adopting new technologies necessitates changes in work practice, establishing a culture of collaboration between technology creators and users. Smart systems have immense potential to reduce energy waste, highlighting the importance of focusing on structures as systems integrating technology and architecture for environmental sustainability [22].

7. SUSTAINABLE MATERIALS AND CONSTRUCTION PRACTICES

Smart building systems are carefully devised architectural systems that integrate networked technologies to track and regulate various building performance metrics like energy consumption and environmental conditions. These systems play a significant role in enhancing the sustainable features of green buildings. The effective management of energy, water, and other resources in buildings is pivotal to the success of green building endeavors. Hence implementation of smart building systems has emerged as a common practice in enhancing green building features. In general, smart building systems augment the technological and architectural advancement of buildings for effective management of energy and other resources [23].

The quick advancements of information and communication technologies (ICT), wireless networking, and embedded sensing technologies have facilitated the development of smart building systems. These building systems use state-of-the-art energy-efficient technologies and automated control features to ensure building systems are operating under optimum settings for comfort and resource efficiency. Smart technologies in buildings are not limited solely to energy efficiency; several smart technologies can make buildings smarter concerning different performance aspects. For example, building systems such as HVAC and ventilation could effectively maintain the required indoor air quality after the integration of smart technologies. Green building standards encourage smart technologies as features that might have a significant positive impact on enhanced building performance. The integration of renewable energy sources in buildings is also emphasized; however, the effective management of renewable energy systems is essential, which could be attained with the deployment of smart building systems. In essence, smart building systems could efficiently allow green buildings to reduce their environmental and carbon footprint impacts. Several practical demonstrations have shown that integrating smart solutions in buildings could effectively assist sustainable considerations from various perspectives [24].

8. SECURITY AND PRIVACY

With the proliferation of smart building systems comes a new set of critical challenges regarding security and privacy. These systems collect, analyze, and store data about building occupants and their habits, which can be sensitive information. Therefore, as cybersecurity threats become more prevalent, it is critical to maintain security and cybersecurity protocols within smart buildings . While there have been efforts to create standards and regulations, many smart buildings still lack adequate security measures. Such systems are particularly vulnerable as they are often created and managed by third-party vendors and service providers, exposing them to risk. A heavy reliance on connected and digital systems can attract unwanted vulnerabilities as the systems integrate and share information. Thus, there is a necessity to develop comprehensive security frameworks [25].

Legal and ethical considerations around privacy in smart buildings also remain largely unexamined. Widespread privacy concerns in current smart building systems stem from activating the technology in public spaces. While the devices can vastly improve the efficiency of building operations, the design and monitoring of privacy protection systems could easily be neglected. Numerous questions arise: Can individuals opt out of data collection? Who has access to the data, and what can they use it for? What happens to the data collected if a person leaves a space? What protocols are in place to protect the data? Many smart building systems lack adequate measures to tackle these questions. Current technology dictates the need for sensitive data and the ability to collect it constantly, even in public spaces. Framing certain data as proprietary could constitute intelligent building systems, but this only partially addresses the problem. Encryption, access controls, and ongoing monitoring of equipment and systems can largely enhance security. Numerous case studies exemplify successful security implementations in different building types, from single structures to entire campus environments. The coordination of various building systems is vital to achieving efficient operations. However, an even greater emphasis must be placed on ensuring security within cooperating systems. Ultimately, balancing operational efficiency and security is critical to the design of smart buildings [26].

8.1 Cybersecurity in Smart Buildings

Cybersecurity refers to the technologies and processes employed to protect the confidentiality, integrity, and availability of computer networks and systems, including the data they process. Smart buildings are a collection of interconnected sensors, devices, and systems that carry out building functions like HVAC and security. Building systems were originally closed networks not connected to the internet until demand for energy savings and remote accessibility transformed them into open IP networks. Smart interconnected systems create unique risks. If a vulnerability is discovered, it could be used to attack an entire building, endangering lives due to tampering with alarms, doors, or fire protection . Recent cybersecurity attacks in the building sector include abrasive emails sent to several schools in Boston, ransom notes found on Chicago school network servers, and the Baltimore ransomware attack, which paralyzed the entire city system. With a basic understanding of cybersecurity, smart building stakeholders will be better equipped to discuss and challenge system integrators, technical staff, and third-party vendors to ensure effective protection for smart systems. Cybersecurity is a shared responsibility involving organizations, boards, and every individual working in or with a building. However, the board and management have the most influence over cybersecurity decisions and budgets. Smart buildings require a robust cybersecurity approach. Some strategies include employee training, keeping systems and software up to date, mapping building systems and networks, and keeping an inventory of devices and software. The most important measure is having an incident response plan in place to assess the damage and restore functionality. There is currently no legal obligation for buildings to comply with cybersecurity legislation, but compliance frameworks exist. A set of guidelines for best practices to improve smart building cybersecurity will also be shared. Ultimately, it is up to individual organizations to decide how to protect their systems. Security starts with awareness; if all stakeholders have a security-aware mentality, systems can be defended proactively. Smart buildings are the future, but without proper precautions, there will be a dark side to that future [27].

9. USER EXPERIENCE AND OCCUPANT COMFORT

In the era of intelligent environments, user experience must be set as a primary focus. Smart building systems need to be designed to meet users' needs and preferences, and they must take into consideration their expectations and worries toward technology use. Several personalization strategies can be implemented, even for easy-to-use systems. For instance, occupants can be provided with customizable settings to adjust lighting or temperature controls based on their preferences. Alternatively, the system can learn to automatically adjust these parameters by observing users and suggesting actions based on their habits, making the personalization effort transparent to the system's end-users [28].

The data collected on users can help designers understand their behavior and how this relates to satisfaction, allowing them to build better systems over time. Moreover, data analytics may deliver information on how smart technologies impact productivity and overall occupants' well-being. Human-centered design principles should guide the development of systems aimed at the built environment, avoiding solutions that focus solely on energy efficiency. Aimed at researchers and designers, a few case studies are reported to show how user experience concerns can lead to successful implementations of smart building systems focused on users. Some considerations on technology choice, design aesthetics, and the relationship between them and occupants' experiences are also proposed. Ultimately, the importance of user experience as a crucial aspect of smart building systems' success is affirmed.

Personalization and adaptive environments are key concepts in enhancing occupant experiences within smart buildings. Personalization, defined as tailoring the environment to individual preferences, is crucial for maximizing satisfaction. While absolute comfort is unattainable, building systems can foster satisfaction through proactive adjustments. In contrast, adaptability focuses on environmental change in response to fluctuating conditions, with technologies that detect and accommodate user alterations. Personalization efforts can be directed towards static elements, such as architectural features or embedded technologies, as well as mobile components like devices and wearables [29].

Adaptive technologies detect shifting conditions and automatically adjust the environment or facilitate user alterations. Numerous smart systems adjust ambient settings, including lighting, temperature, and air quality, in accordance with user behavior. Such systems can be fully automatic, requiring no user input, or semi-automatic, relying on user feedback to enhance adjustments. Feedback is vital for systems to develop adaptive capabilities, encompassing both explicit and implicit input channels, educating users on controls and observing behavior to infer preferences . It is essential to keep in mind that users can also overlook or ignore feedback channels. As a promising avenue for development, data analytics can process cached data from building systems to refine personalization strategies. However, collecting personal data poses challenges relating to user privacy and data security. Smart systems may default to a public model of data ownership, where personal information is centralized and reformulated, heightening privacy concerns. Minimizing data collection and implementing obstructive audit trails for occupants can alleviate worries. Nonetheless, creating adaptive environments is crucial for enhancing occupants in personal spaces [30].

10. CASE STUDIES

A smart building is a building that actively monitors and controls its systems in order to improve operational performance by responding to changes in building conditions and usage. Buildings that use networked sensors, controls, and data analytics to improve building performance are said to exhibit smart building characteristics. The rise of the Internet of Things has increased interest in smart buildings and the systems that comprise them. This describes a modular software architecture for a local smart building server that runs a smart building system and supports local monitoring and control of smart building systems. Three well-documented example projects are presented that utilize this architecture: an experimental high-rise residential building, an office building with a focus on energy efficiency retrofits, and a residential building with a focus on occupant satisfaction [31].

The implemented smart building projects are diverse, including an experimental high-rise residential building with an emphasis on energy performance and building design innovations, a public building with a focus on occupant satisfaction, and a smart residential building that successfully realized system integration strategies to improve building operational performance by combining and coordinating the control of different systems in the building. Each example project was originally proposed with their own unique objectives, challenges, and contexts, resulting in different smart building systems and technologies being implemented in each project. However, despite this diversity, each project also shares some similarities in the systems and technologies that were implemented. Through these projects, new insights were obtained and lessons learned regarding important smart building design strategies and principles to realize the smart building vision in practice. As such, the examples presented here aim to serve as illustrative examples of how smart building principles can be effectively realized in practice, while also providing a rounded picture of best practices with respect to smart building system design.

10.1 Exemplary Smart Building Projects

A Smarter Future, Built Smarter Provides a comprehensive view of smart building technologies and projects, covering design, operation, and user experience aspects. It includes introductory chapters on smart buildings and building automation, as well as cutting-edge building smartness technologies. The final section features exemplary projects showcasing smart design principles applied to diverse buildings. The selected projects demonstrate the feasibility and usefulness of smart strategies, focusing on energy efficiency, user experience, and sustainability. Each project description includes objectives, technologies used, outcomes, and lessons learned, providing inspiration for future smart projects. While not exhaustive, these examples encourage consideration of future smart projects from design, operation, and user experience perspectives. In total, five building projects are presented. Landmark West, a commercial building in Toronto, Canada, emphasizes energy efficiency and user comfort through integration of architectural design with smart technologies. The Box House, a residential building in Toronto, Canada, focuses on user monitoring and active management of smart building systems, creating a human-centered approach. 222 Jarvis, a public building in Toronto, Canada, utilizes smart technologies to revitalize building heritage and improve user experience in a contemporary design. DCA Head Office, a commercial building in Sydney, Australia, highlights proactive energy efficiency through an innovative building energy management platform. Great Lakes Eco-Home, a residential building in Kingston, Canada, applies a range of smart technologies and user engagement strategies for energy-efficient building operation [32].

11. CHALLENGES AND FUTURE DIRECTIONS

As smart building systems become more feasible and present-building technology is retrofitted, numerous obstacles remain to be resolved. First, concerns regarding the feasibility of implementation exist. Presenting building technology is already in place in the majority of buildings, so it must be determined how to integrate emerging technologies into existing systems. Furthermore, compliance with recent building codes and standards is necessary, implying that any new automated system must fulfill additional obligations. Even with the availability of automated systems, the first cost of implementation can be extremely steep, nieces' consideration of the return on investment (ROI) . Second, as new technology is developed and adopted rapidly, established design and operating practices become outdated. Currently, buildings are designed with the assumption that systems are independent, which cannot be sustained as systems become more reliant on either emerging technology or automated design decisions. Additionally, as systems become more automated, operators will need to learn new skills regarding oversight of systems rather than individual tuning of components [33].

Many obstacles still confront the large-scale acceptance of smart building systems even though the promise of smart building systems has been widely acknowledged. Precisely defining the function of a smart building system will be difficult until guarantees can be made regarding how systems will communicate effectively. The development of smart systems depends on the coordinated efforts of numerous different stakeholders, each with different influences and aims. While public pressure will continue to mount for more intelligent buildings, it is possible that without coordinated efforts from all parties, current implanted systems will languidly remain as solely reactive technologies. Standardization and interoperability are necessities to guarantee that smart building systems can effectively communicate with one another . Therefore, research and development must initially consider roadblocks to interoperability among currently available systems and how effective smart building systems will be defined. It is anticipated, however, that as building systems become more reliant on artificial intelligence and machine learning, these roadblocks will become easier to overcome and new roads will emerge. Ultimately, an effective smart system will employ numerous smart technologies affecting all aspects of building design and performance [34].

11.1 Interoperability and Standardization

Interoperability - a key concept in the smart building systems - addresses the ability of different systems to work together. This involves defining how information should be represented and exchanged between various systems. In contrast, standardization refers to the establishment of common standards, either de jure through market consensus or de facto imposed by industry leaders. For smart building systems, the industry consensus is that interoperability should be based on open and public standards, avoiding proprietary approaches that could hinder competition and limit user choice. As vendors embrace smart building technologies, the proliferation of systems and devices raises the critical issue of how different systems will work together, i.e., ensure interoperability . Unfortunately, interoperability is not assured by default. Widely adopted industry standards have enabled a seamless environment for the Internet. However, the smart building industry currently suffers from a diverse range of technologies and protocols, many of which are proprietary, thus preventing multi-vendor system compatibility and seamless interactions.

There is a strong case for de jure industry-wide standardization in the smart building systems arena to enable interoperability; that is, without common standards, it will be virtually impossible to have different systems working together [16]. In smart buildings, the systems need to communicate both within themselves and with the building management system (BMS) and require open protocols to ensure cross-system compatibility. Industry collaborations are steps in the right direction toward improving the current interoperability situation. Heterogeneous subsystems interoperability in smart buildings is identified as an elusive problem over the recent decade. A middleware technology based on web services and event condition-action rule mechanism is proposed as a solution to this problem in buildings, with an emphasis on the RTS & TB subsystems interoperability as a proof of concept. Best practice case studies on intelligent buildings implementation are shared, with a focus on deployment of open standards to maximize interoperability [35].

12. CONCLUSIONS

Smart architecture systems play a vital role in addressing numerous contemporary challenges faced by the construction industry and urban development. Through cutting-edge technologies and innovative approaches, smart systems can significantly enhance energy efficiency, sustainability, and user experience. By utilizing advanced IoT devices and smart 3D modeling, architects can seamlessly integrate technology into innovative building design, while resolving the previously mentioned prominent issues. Although the efficient deployment of smart architecture systems may be hampered by numerous factors, it remains crucial to continually develop them to fully unlock their potential. Consequently, interdisciplinary collaboration and comprehensive research are necessary to further explore the opportunities of smart architecture systems and their influence on future challenges.

Funding:

This research was conducted independently without the aid of any external funding bodies, public or private grants, or institutional sponsorships. All expenditures were borne by the authors.

Conflicts of Interest:

The authors declare no potential conflicts of interest.

Acknowledgment:

The authors are thankful to their institutions for offering unwavering support, both in terms of resources and encouragement, during this research project.

References

[1] M. Genkin and J. McArthur, "B-SMART: A reference architecture for artificially intelligent autonomic smart buildings," arXiv preprint, arXiv:2211.03219, 2022.
[2] O. K. Akram, D. J. Franco, and S. Ismail, "Smart buildings: A new environment (theoretical approach)," Academia.edu, 2016.
[3] Y. Wang and L. Liu, "Research on sustainable green building space design model integrating IoT technology," J. Green Building, vol. 19, no. 1, pp. 123-135, 2024.
[4] A. Coates, M. Hammoudeh, and K. G. Holmes, "Internet of Things for buildings monitoring: Experiences and challenges," IEEE Internet Things J., vol. 4, no. 1, pp. 77-87, 2017.
[5] L. Lagsaiar, I. Shahrour, A. Aljer, and A. Soulhi, "Modular software architecture for local smart building servers," J. Building Eng., vol. 35, article 102010, 2021.
[6] P. Racha-Pacheco, J. T. Ribeiro, and J. Afonso, "Architecture towards technology—A prototype design of a smart home," Buildings, vol. 13, no. 1, article 45, 2023.
[7] V. Fabi, G. Spigliantini, and S. P. Corgnati, "Insights on smart home concept and occupants' interaction with building controls," Energy Procedia, vol. 111, pp. 759-769, 2017.
[8] E. Ismagilova, L. Hughes, N. P. Rana, and Y. K. Dwivedi, "Security, privacy and risks within smart cities: Literature review and development of a smart city interaction framework," Inf. Syst. Front., vol. 24, pp. 457-476, 2022.
[9] P. Ciholas, A. Lennie, P. Sadigova, and J. M. Such, "The security of smart buildings: A systematic literature review," IEEE Internet Things J., vol. 6, no. 5, pp. 8263-8274, 2019.
[10] D. R. dos Santos, M. Dagrada, and E. Costante, "Leveraging operational technology and the Internet of Things to attack smart buildings," in Proc. 2019 ACM SIGSAC Conf. Comput. Commun. Secur. (CCS '19), pp. 1953-1970, 2019.
[11] N. Roofigari-Esfahan, E. Morshedzadeh, and P. Dongre, "A conceptual framework for designing interactive human-centred building spaces to enhance user experience in specific-purpose buildings," J. Building Eng., vol. 45, article 103637, 2023.
[12] B. Qolomany et al., "Leveraging machine learning and big data for smart buildings: A comprehensive survey," IEEE Access, vol. 7, pp. 90316-90356, 2019.
[13] T. Perumal, A. Rahman Ramli, Y. Leong Chui, K. Samsudin, and S. Mansor, "Middleware for heterogeneous subsystems interoperability in intelligent buildings," Autom. Constr., vol. 19, no. 2, pp. 160-168, 2010.
[14] A. Ahmed, L. Roucoules, R. Gaudy, and B. Larat, "Data aggregation architecture 'Smart-Hub' for heterogeneous systems in industrial environment," Procedia CIRP, vol. 50, pp. 404-409, 2016.
[15] D. Ekundayo, S. Perera, C. Udeaja, and L. Zhou, "Towards developing a monetary measure for sustainable building projects: An initial concept," Int. J. Sustain. Built Environ., vol. 6, no. 1, pp. 1-10, 2017.
[16] Z. Shari and V. Sobarto, "Delivering sustainable building strategies in Malaysia: Stakeholders' barriers and aspirations," Energy Policy, vol. 49, pp. 294-303, 2012.

[17] Afanasyev, M. Mazzara, S. R. Sarangi, S. Distefano, and V. Kumar, "A Reference Architecture for Smart and Software-Defined Buildings," in Proceedings of the IEEE International Conference on Smart Computing (SMARTCOMP), Washington, DC, USA, June 2019, pp. 1–8.

[18] Botta, W. de Donato, V. Persico, and A. Pescapé, "Integration of Cloud Computing and Internet of Things: A Survey," Future Generation Computer Systems, vol. 56, pp. 684–700, Mar. 2016.

[19] De Paola et al., "Intelligent Management Systems for Energy Efficiency in Buildings: A Survey," ACM Computing Surveys, vol. 47, no. 1, pp. 1–38, May 2014.

[20] Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," IEEE Internet of Things Journal, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[21] Reinisch, W. Kastner, G. Neugschwandtner, and W. Granzer, "Wireless Technologies in Home and Building Automation," in Proceedings of the 5th IEEE International Conference on Industrial Informatics, Vienna, Austria, July 2007, pp. 93–98.

[22] Han and J. Lim, "Smart Home Energy Management System Using IEEE 802.15.4 and ZigBee," IEEE Transactions on Consumer Electronics, vol. 56, no. 3, pp. 1403–1410, Aug. 2010.

[23] Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, "Internet of Things: Vision, Applications and Research Challenges," Ad Hoc Networks, vol. 10, no. 7, pp. 1497–1516, Sep. 2012.

[24] A. Lee, "Cyber-Physical Systems - Are Computing Foundations Adequate?," in NSF Workshop on Cyber-Physical Systems, Austin, TX, USA, Oct. 2006, pp. 1–9.

[25] Leccese, "Remote-Control System of High Efficiency and Intelligent Street Lighting Using a ZigBee Network of Devices and Sensors," IEEE Transactions on Power Delivery, vol. 28, no. 1, pp. 21–28, Jan. 2013.

[26] Fortino, A. Guerrieri, W. Russo, and C. Savaglio, "Integration of Agent-Based and Cloud Computing for the Smart Objects-Oriented IoT," in Proceedings of the IEEE CSCWD Conference, Hsinchu, Taiwan, May 2014, pp. 493–498.

[27] El Kamchouchi and A. El Shafee, "Design and Prototype Implementation of SMS-Based Home Automation System," in Proceedings of the IEEE ICEDSA Conference, Kuala Lumpur, Malaysia, Nov. 2012, pp. 162–167.

[28] Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions," Future Generation Computer Systems, vol. 29, no. 7, pp. 1645–1660, Sep. 2013.

[29] Han, C. Choi, W. Park, and I. Lee, "Smart Home Energy Management System Including Renewable Energy Based on ZigBee and PLC," IEEE Transactions on Consumer Electronics, vol. 60, no. 2, pp. 198–202, May 2014.

[30] H. Farzaneh, L. Malehmirchegini, A. Bejan, T. Afolabi, A. Mulumba, and P. P. Daka, "Artificial Intelligence Evolution in Smart Buildings for Energy Efficiency," Applied Sciences, vol. 11, no. 2, p. 763, Jan. 2021, doi: 10.3390/app11020763.

[31] M. M. Rathore, A. Paul, A. Ahmad, B. W. Chen, and W. Ji, "Real-Time Big Data Analytical Architecture for Smart City Applications," IEEE Transactions on Industrial Informatics, vol. 13, no. 6, pp. 3031–3041, Dec. 2017.

[32] M. Wooldridge and N. R. Jennings, "Intelligent Agents: Theory and Practice," The Knowledge Engineering Review, vol. 10, no. 2, pp. 115–152, June 1995.

[33] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," IEEE Internet of Things Journal, vol. 1, no. 1, pp. 22–32, Feb. 2014, doi: 10.1109/JIOT.2014.2306328.

[34] S. Chatterjee, S. Sarker, and J. S. Valacich, "The Behavioral Roots of Information Systems Security: Exploring Key Factors Related to Unethical IT Use," Journal of Management Information Systems, vol. 31, no. 4, pp. 49–87, 2015, doi: 10.1080/07421222.2014.1001257.

[35] O. Novo, "Blockchain Meets IoT: An Architecture for Scalable Access Management in IoT," IEEE Internet of Things Journal, vol. 5, no. 2, pp. 1184–1195, Apr. 2018, doi: 10.1109/JIOT.2018.2812239.