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Smart City Architecture Technologies: Challenges and Prospects

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Abstract: The article deals with the analysis of smart city architecture technologies, with the focus on the role of buildings as active elements in the digital urban environment. It examines the key components of smart architecture, including IoT, BIM, and cloud platforms, and their integration for the dynamic management of building operational processes. It reviews the advantages and limitations of digital technologies, including energy efficiency, automation, security, and user comfort. Particular attention is paid to identifying current problems: interoperability, data privacy, network delays, limited device resources, and scalability. Several approaches to solving these problems are presented, including federated learning, blockchain, and adaptive architecture, which ensure the comprehensive, sustainable, and secure operation of smart buildings.

Keywords: smart city, adaptive architecture, Internet of Things, building information modelling, BIM, cloud computing, energy efficiency, smart buildings.

The smart city is a modern urban concept that emerged in the post-industrial era amid the widespread digitalisation and active development of information and communication technologies (ICT). The emergence of this concept was a response to the challenges and threats of our time: the environmental crisis, dynamic urbanisation, growth and expansion of megacities, social stratification, international terrorism, economic crises, and global competition.

Initially, the smart city was perceived exclusively as an urban ecosystem saturated with high technologies. However, over time, it has become clear that technologies alone do not make a city “smart”. In recent years, the formation of smart cities and their various models has come to be seen as an effective solution to the task of combining intelligent technologies and sustainability. A number of opinions emphasise that the smart city is not just about technological progress – it goes far beyond that. Sustainable development goals are an integral part of the smart city concept [1, p. 7].

In addition, scientists who examine this concept from a scientific point of view are focusing not only on the issues of modern infrastructure and information technologies but also on the importance of human capital. The British Standards Institution describes the smart city as a combination of various systems (human, physical, information, and others) and their organisation in the most efficient way possible to achieve a sustainable, highly intelligent, convenient, and comfortable future for the city’s citizens [2, p. 7].

It would not be an exaggeration to assume that architecture occupies a central place in the smart city landscape. In the context of digital transformation, it becomes a key interface between digital technologies, urban infrastructure, and everyday practices of city dwellers. A network of architectural complexes forms a spatial framework for the implementation of intelligent services, distributed sensor networks, automated control systems, people/city interaction technologies, and sustainable development mechanisms.

The technical framework of smart cities includes the Internet of Things (IoT), sensor systems, artificial intelligence, machine learning, digital twins of buildings and urban areas, big data systems, cloud computing, as well as algorithms of predictive analytics and automated control. Digital technologies embedded in architecture allow buildings to “sense” the environment, respond to changes in microclimate parameters, regulate energy consumption, optimise engineering systems, ensure safety, and improve the quality of the living environment. A new typology is emerging – the smart building, which functions as an independent intelligent unit of urban infrastructure.

Table 1: An optional architectural structure within a smart city

Criterion	Smart city technologies	Smart architecture technologies
Application scale	Urban and regional levels	Building or building complex level
Main objective	Optimisation of urban infrastructure and services	Improvement of building functionality, comfort and energy efficiency
Data type	Macrodata: traffic, weather, logistics, ecology, transport flows	Microdata: temperature, humidity, movement, energy consumption, CO_2
IoT (Internet of Things) infrastructure	Sensors in transport, on the roads, in lighting facilities, in infrastructural facilities	Sensors in HVAC, lighting, lifts, facades, rooms

AI applications	Traffic management, service demand forecasting, urban activity analysis	Microclimate automation, predictive equipment maintenance
Integration level	Interaction across all areas: transport, energy, security, ecology	Integration of engineering systems within buildings
Communication networks	5G, LoRaWAN, NB-IoT, urban Wi-Fi networks	Wi-Fi, BLE, ZigBee, KNX, BACnet
Energy efficiency	Smart Grid, monitoring of the city’s energy balance	Intelligent HVAC control, energy-active facades
Security	Video surveillance systems, city monitoring centres	Biometric access, automated alarm systems
Sustainability	Emissions control, climate risk management	Use of renewable sources, smart materials
Process automation	Traffic management, street lighting and waste management	Automation of lighting, shade, and ventilation
User’s role	Citizens as participants in the urban digital ecosystem	The user as a controller/adapter of space
Technology types	Smart traffic lights, smart lighting, digital city twins, waste management systems	BMS (Building Management Systems), smart windows, adaptive facades, digital twins of buildings
Economic effects	Reduced infrastructure costs, optimised services, improved urban mobility	Reduced building operating costs, improved operational quality
Environmental functions	Air quality management, organisation of “green corridors” (landscape elements, green spaces connecting parks and gardens, vertical and horizontal greening of buildings), ecosystem monitoring	Low-energy design, indoor emissions control
Architectural solutions	Urban planning with regard to digital flows, smart infrastructure	Integration of digital systems into structural and facade solutions
Technology orientation	Towards social processes and municipal efficiency	Personal comfort and operational optimisation

Despite the obvious advantages of using digital technologies in architecture, they also give rise to new challenges. Firstly, it is necessary to consider the issue of compatibility of the digital and physical layers of the urban environment: how do sensor networks, automated systems, and algorithmic control affect the architectural and spatial structure of the city? Secondly, issues of privacy, reliability, and data security are becoming increasingly relevant, as far as smart city architecture inevitably involves systems for collecting and processing user behaviour information. Thirdly, there is a problem of adapting traditional architectural design methods, which are not always able to take into account the dynamic nature of digital processes changing in real time.

Despite the active scientific research on digital technologies for the urban environment, the analysis of smart city architectural technologies is still insufficient, being far from systemic and interdisciplinary. The existing studies mainly focus on individual aspects: engineering systems, energy efficiency, digital management, and transport models; they rarely consider architecture as an integration platform that unites these elements into a single space. Another problem is that smart city architecture is mainly addressed as a technological object, while its cultural and social components are pushed into the background.

In modern conditions, smart city architecture should be viewed as a multi-level system that combines digital technologies, environmental principles, social processes, and the physical environment. It becomes a space for the interaction of data and space phases, where due designing can shape more efficient, sustainable, and inclusive urban structures.

The present research aims to reveal the technological foundations of smart city architecture, explore its principles, components, and mechanisms for integrating digital solutions into the architectural and spatial structure of the urban environment, and to identify the key problems arising from the use of ICT, as well as the ways to solve these problems.

Thus, **the purpose** of the study is to identify and systematise the technological foundations of smart city architecture and to specify the role of buildings as active elements of the digital urban environment.

To achieve the set goal, the following objectives are being addressed:

1. To analyse the principles and key components of smart city architecture.
2. To investigate the mechanisms for integrating digital technologies into the architectural and spatial structure of the urban environment.
3. To identify the problems in applying ICT in urban architecture, and develop ways to solve them.
4. To clarify the role of buildings as active elements of the smart city system.

Technological Framework of Smart City Architecture

BIM (Building Information Modelling)

BIM is a technology for creating and managing a digital information model of a building that combines architectural, engineering, and construction data at all stages of the life cycle: from design and construction to operation and demolition. In the structure of this model, each aspect of the object contains the following data: geometry, materials, cost, technical characteristics, installation dates, and even operating data.

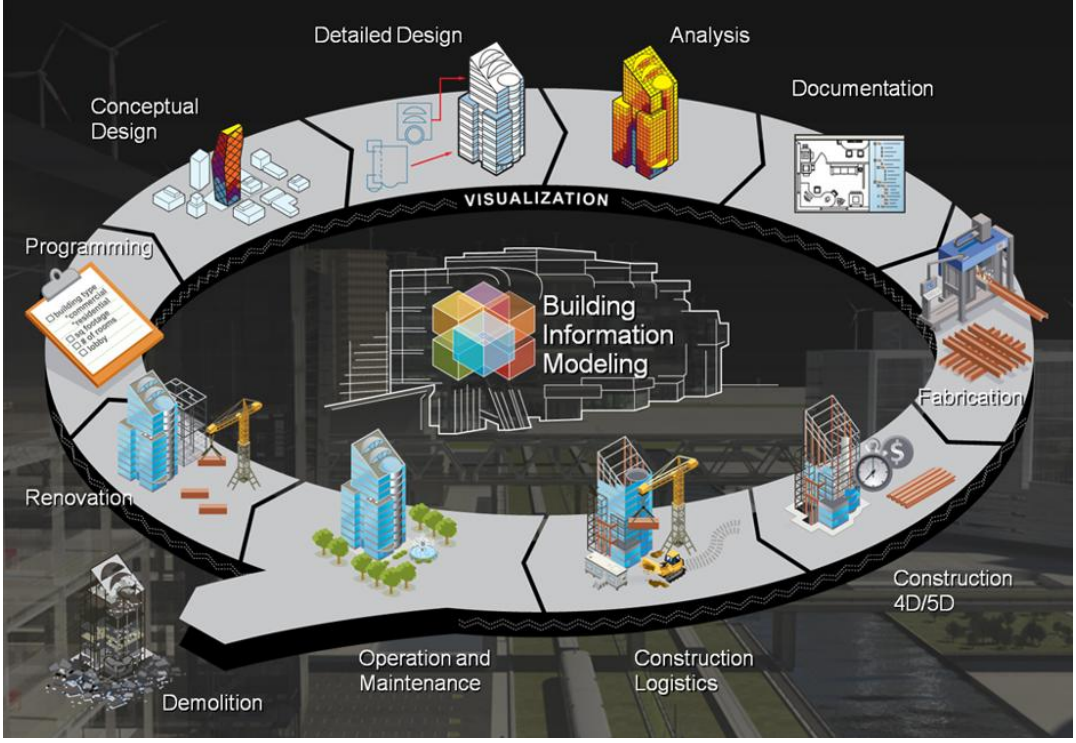


Fig. 1: Schematic representation of BIM technology

The introduction of BIM has enabled all project participants to exchange information using a more advanced technology, which includes parametric modelling and data compatibility. BIM continues to evolve as a data integration tool with multiple “dimensions”: from 3D to 10D. Although 7D–10D dimensions are relatively new and insufficiently studied, they are already recognised as important achievements in the fields of architecture, engineering, and construction.

The best-known BIM dimensions include:

- **3D** – visualisation of architecture, structures, and materials;
- **4D** – planning of construction time and schedules;
- **5D** – cost and resource management;
- **6D** – assessment of sustainability and energy efficiency;
- **7D–10D** – operation and safety management, flexible construction, and industrialisation.

In the context of a smart city, BIM technology makes it possible to reproduce dynamic data in real time in 3D format, monitor the state of the construction industry, make prompt decisions, and control energy supply and consumption in city buildings.

In the short term, BIM helps to save money by correcting errors identified before construction begins. In the medium term, it provides better control over the functionality of a building. According to the Integrated Engineering Centre, BIM technologies:

- Reduce project implementation time by 30%;
- Reduce costs by 10% through early prevention of collisions;
- Reduce estimate development time by 80%;
- Increase estimate accuracy by 3%;
- Reduce waste and defects by 30%.

The main economic benefits of using BIM are:

1. Reduced costs and risks;
2. Acceleration of design and construction with increased manageability;
3. Potential for high return on investment;
4. New sources of income through services;
5. Construction mobility with safety compliance

In terms of social impact, BIM improves coordination between construction participants at all stages of the building's life cycle (design, erection, operation). Architects, engineers, contractors, customers, and operators work in a unified digital environment, which allows them to coordinate actions, form common expectations, and agree on investment decisions offered by different organisations [3, pp. 76–79].

Despite the potential of BIM technologies and selective positive cases of their use [3, pp. 80–84], a number of studies show that their application faces systemic barriers [4, 5, 6, 7]. The most comprehensive overview of the key problems is provided by Kaur et al. [7].

The authors identify a set of interrelated barriers to BIM implementation, the key ones being interoperability gaps between different BIM platforms and the underutilised potential of plugin ecosystems, as well as the lack of factual, real-life examples of BIM application during the renovation and operation of buildings that were not originally modelled. At the same time, many popular solutions, in particular Revit (a software platform for BIM, which was designed to create and control parametric BIM models of architectural, structural, and engineering systems), remain limited in terms of infrastructure design in virtue of their focus on vertical structures. Other significant problems include uncertainty regarding data ownership and property rights, the lack of unified workflows, insufficient key stakeholder involvement, high start-up costs of implementation and staff training, poor competencies, especially at the management level, as well as unresolved legal and contractual issues related to the distribution of functions and responsibilities. In addition, one can observe a low level of applying BIM in residential construction, especially in developing countries, and a limited use of its potential in green and energy-efficient buildings, primarily in small-scale projects, due to their high cost and the complexity of the involved tools. Finally, there are problems of scalability and compatibility of open API for BIM systems (application programming interfaces designed for accessing, managing, and automating work with BIM model data), which are not always suitable for complex analytical tasks and automated security checks. At the same time, the explorers note that managerial, technical, and personnel constraints reinforce each other [7, p. 52, 167–232].

The problems do not exist in isolation: the lack of employee knowledge makes it difficult to work with new platforms, which in turn increases the risk of errors and brings down trust in digital systems. Similarly, technological limitations and interoperability gaps hinder the comprehensive integration of systems, increasing the need for specialised skills to overcome them.

To systematise the approaches to addressing these challenges, the following set of strategies is proposed, presented in tabular form:

Table 2: Systematisation of BIM application problems and the ways to resolve them

Problem	**Solution**
Insufficient staff competencies and knowledge	Interdisciplinary educational programmes, training courses, seminars, mentoring
Interoperability gaps and technological constraints	Use of open standards (IFC, COBie), development of plugins and APIs, integration with cloud platforms
High start-up costs and uncertain economic benefit	Pilot projects in demonstration mode, phased introduction of BIM, use of governmental and industry-specific incentive mechanisms
Resistance to change and lack of management support	Strategic change management, involvement of top executives, fostering a corporate culture of innovation

Legal uncertainty and lack of standards	Development of legal framework and BIM contracts, clear definition of functions and responsibilities, introduction of corporate model exchange protocols
Limited application of BIM in sustainable construction	Active introduction of BIM in energy-efficient designing, pilot green construction projects, training in the basics of sustainable architecture

The presented problems and proposed solutions, as set forth in the table, demonstrate that the successful implementation of BIM in smart buildings is impossible without a comprehensive approach that combines technical, organisational, and legal aspects. Strategic change management, involvement of top management, and the formation of a corporate innovation culture create a basis for overcoming resistance to change. The development of a legal framework and BIM contracts, as well as the implementation of corporate model exchange protocols, ensure legal certainty and consistency of all project participants' actions. At the same time, the active use of BIM in sustainable construction through pilot projects and training in energy-efficient design principles contributes to the integration of green technologies and reduces the environmental impact associated with buildings.

However, digital models as such and standards for working with them cannot fully ensure intelligent building management without a constant flow of data showing the condition of facilities and user behaviour. This is where the IoT technology comes to the fore.

IoT (Internet of Things)

IoT is an integrated network of interconnected devices capable of autonomously collecting, transmitting, and processing data without direct human involvement. Sensor modules of IoT devices record various physical parameters, including temperature, humidity, movement, and pressure. The captured data are transmitted via network protocols, such as Wi-Fi, Bluetooth, LoRa, and 5G, to centralised or cloud platforms, where they are subjected to analytical processing. The processing helps to identify due patterns, forecast due needs, and enables automated control of networked objects. The interaction with the system is effectuated through specialised interfaces and control panels that provide monitoring, control, and operational access to the data obtained during the analysis.

In the context of smart buildings, IoT is implemented through the comprehensive integration of sensor, executive, and computing components aimed at automating and optimising the operation of facilities. The central subsystem is HVAC (heating, ventilation, and air conditioning), which operates on the basis of sensor module data analysis, which ensures the maintenance of comfortable microclimatic conditions while minimising energy consumption through adaptive control of equipment operation depending on the actual load and the presence of consumers. Similarly, lighting systems equipped with motion and illuminance level sensors provide dynamic adjustment of light intensity, helping to reduce energy costs.

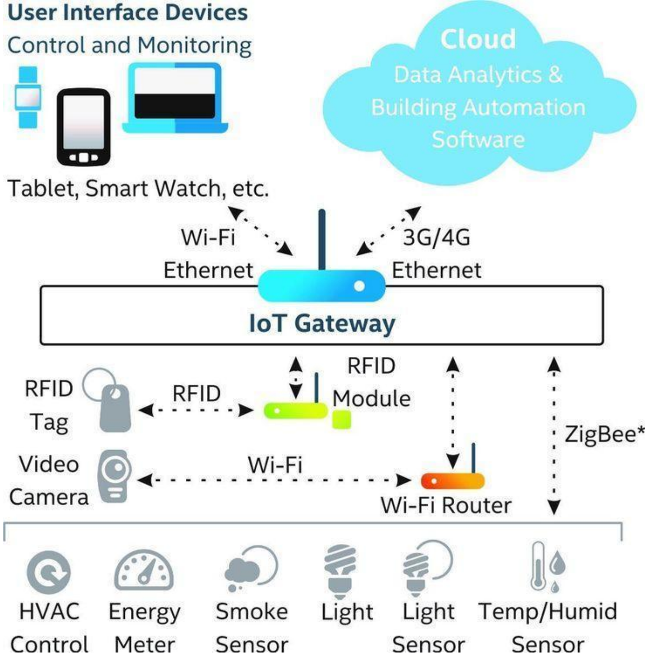


Fig. 2: Schematic representation of IoT implemented in a building

Security systems, including video surveillance, motion sensors, security and fire protection devices, are integrated with the IoT platform for round-the-clock monitoring, automatic response to incidents, and transmitting relevant information to persons in charge. In addition, resource consumption, including electricity and water, is monitored, with the generation of analytical reports and forecasts. This contributes to increased energy efficiency, optimised operating costs and maintenance planning.

Various types of sensors, run-time modules, and identification devices are important components of IoT systems in smart buildings. Among them, RFID tags and readers are of particular importance, as they enable automatic identification of objects, equipment, and personnel without physical contact, allowing for real-time monitoring, access control, and movement tracking.

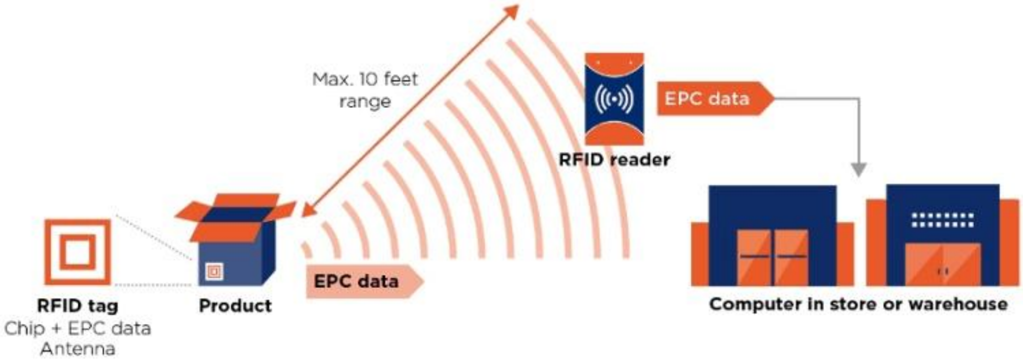


Fig. 3: Device interaction sequence in the chain RFID tag – the user

Sensors recording temperature, humidity, motion, illuminance, and CO_2 collect information about the state of the environment, allowing HVAC and lighting systems to adapt to current conditions and the presence of people. Run-time modules (actuators) automatically regulate the operation of equipment – opening or closing ventilation valves, turning lighting on or off, and regulating heating and air conditioning. All these components interact via the IoT platform, integrate with AI analytical modules, and form an intelligent infrastructure capable of forecasting, automated control, and optimisation of building operating processes.

Thus, IoT technologies, which combine sensors, RFID tags, and executive modules, transform buildings into intelligent objects that provide comprehensive environmental monitoring, forecast technical requirements, and ensure automated control, increasing efficiency, sustainability, and comfort for users.

The compatibility of IoT and AI enhances the effectiveness of these systems by providing intelligent analysis of collected data. AI processes information about temperature, lighting, human presence, and energy consumption to predict needs, optimise HVAC, illumination, and other systems, identify anomalies, and reduce energy losses. The integration of IoT and AI enables real-time decision-making, improves energy efficiency and user comfort, and creates opportunities for automated management of operational processes.

However, despite significant advantages, the implementation of IoT and AI in smart buildings faces a number of problems and limitations. Below is a table with the classification and description of the main challenges.

Table 3: Systematisation and description of the main problems of applying IoT and AI [8, p. 4].

Problem	**Description**
High initial costs	Need for significant investment in equipment, software and infrastructure, which limits its implementation by small businesses and low-income communities.
Limited scalability	The solutions are predominantly designed for individual buildings or regions; integration across entire territories is difficult.
Absence of universal standards	Compatibility issues between IoT devices and AI algorithms increase costs and reduce system efficiency.
Data privacy	Collection and analysis of large amounts of information raises ethical issues and the risk of unauthorised use of personal data.
Cybersecurity	IoT networks are vulnerable to hacking, which can lead to power grid failures, outages, and data breach.
AI algorithmic bias	Systems can distribute benefits unevenly across groups or types of buildings, exacerbating social inequality.

Energy inequality	More affluent areas adopt technologies faster, widening the gap between regions in access to energy-efficient solutions.
Job losses	Automation reduces the need for manual monitoring and maintenance, which can lead to job losses.
Ethical issues	AI may prioritise efficiency over human well-being, for instance, by reducing heating to save energy.
Dependence on cloud services	Cloud analytics creates risks of outages; data ownership issues, and increased operating costs.
Environmental impact of IoT	The manufacture, maintenance, and utilisation of devices increase electronic waste and energy consumption.
Regulatory gaps	Rapid technological development is outpacing regulatory and legal framework, creating uncertainty in the issues of compliance and liability.
User trust and acceptance	Many users and building managers are sceptical about AI-based automation, fearing loss of control, misuse of data, and dependence on technologies.
Lack of long-term research	Most AI-IoT research focuses on short-term benefits; there is insufficient data on long-term performance, reliability, and cost effectiveness.
Ethical management of AI	Lack of governance constraints ensuring transparency, fairness, and accountability of AI, which can lead to unintentional negative consequences for users and society.

The issues listed above demonstrate that the implementation of IoT and AI technologies in smart buildings faces not only technical barriers but also economic, social, and ethical constraints. The diversity of challenges – from the absence of standards, cybersecurity threats to environmental impact and lack of user trust – points to the need for a comprehensive approach that encompasses the architectural, technological, regulatory, and organisational aspects of operating intelligent systems. That is why scientific literature pays considerable attention to the development of solutions aimed at overcoming these limitations and creating a sustainable, scalable, and secure environment for applying IoT and AI in smart buildings. In recent years, several approaches that solve these problems partially or completely have been proposed and tested.

One of the key methods is **federated learning**, which provides distributed training of AI models directly on IoT devices or edge servers without transferring all raw data to the cloud. This approach increases the level of confidentiality, reduces the risk of personal data leaks, and reduces energy consumption through local processing. As an example, the study [9, pp. 4–10] implements EAFL architecture with dynamic client selection and model update quantisation, which makes it possible to optimise energy consumption through distributed analytics.

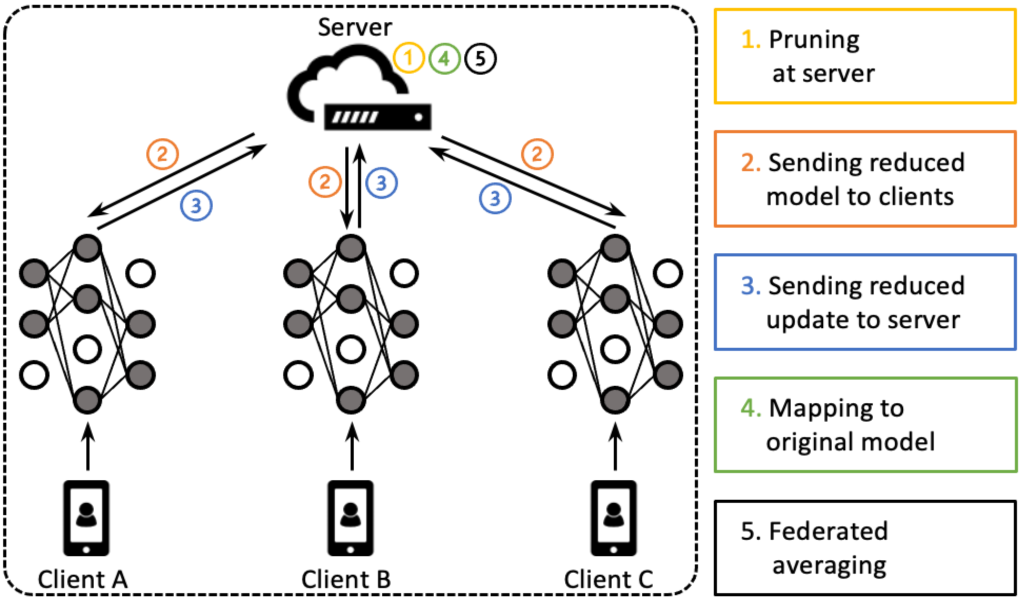


Fig. 4: Schematic chart of federated learning technology

Blockchain technology is actively used to address data security and integrity issues. Blockchain ensures the immutability of records, distributed storage, and protection of information from unauthorised access. Within the framework of scalable urban IoT infrastructure, blockchain is combined with federated learning, which allows for the development of secure and decentralised energy consumption management systems [10, pp. 6–8]. Additionally, hybrid consensus algorithms (PoS + PBFT) and uncomplicated IoT protocols (MQTT, CoAP) are used, which improves system scalability and reduces energy consumption [11, pp. 7–10].

To optimise the operation of a large number of IoT devices, **consumption clustering** and **data processing** methods are used. Grouping devices and users according to similar patterns allows managing the load on the power system, implementing demand-response strategies, and improving resource management efficiency [11, p. 11].

Another important approach is the use **of edge computing**, which reduces latency, decreases the load on cloud services, and increases the system’s resilience to communication failures. In combination with quantisation and compression of AI model updates, this achieves a significant reduction in the amount of transmitted data and consumed energy [9, p. 5].

In addition, **formal security verification methods and cryptographic mechanisms**, including access control and data encryption, are investigated to provide reliable protection of IoT infrastructure against cyberattacks [10, p. 7].

Thus, the integration of federated learning, blockchain, edge computing, clustering methods, and cryptographic protection forms **a multi-level architecture for smart buildings’ intelligent management**, capable of solving the main problems of IoT and AI systems. These approaches ensure data confidentiality and security, scalability, energy efficiency, and operational sustainability, which are critical for implementing intelligent, secure, and sustainable energy management in modern buildings.

At the next level of smart system implementation, adaptive architecture begins to play a central role.

Adaptive Architecture

Adaptive architecture in smart buildings is a dynamic organisational structure comprising engineering and digital systems in a building; it can automatically change its configuration and operating mode in response to changes in external conditions, internal loads, and user behaviour. It is represented as an integrated system that comprehensively utilises the capabilities of the IoT, BIM, and cloud technologies to provide dynamic, autonomous, and optimised management of operational processes.

In this architecture, IoT devices (temperature, humidity, light and motion sensors, energy meters, RFID tags) continuously collect data on the condition of the building, user behaviour and the external environment. These data are transmitted via secure communication channels to cloud platforms that are engaged in large-scale analytics, processing of large amounts of information, as well as forecasting of energy consumption, HVAC system loads, lighting, and other engineering networks.

At the same time, a BIM model of the building is used, which acts as a digital twin of the object and is integrated with IoT and cloud analytics. BIM provides a structured representation of all physical and functional components of the building, including engineering systems, construction elements, and spatial characteristics. This allows the system to understand the context of operation: for instance, the layout of the premises, the air volume to be conditioned, or the areas used intensively.

Cloud technologies provide:

- scalable data processing;
- storage of past information for long-term analysis;
- joint operation of multiple AI algorithms and control systems;
- remote monitoring and control of the building’s condition.

The combined use of IoT, BIM, and the cloud allows adaptive architecture to:

- respond promptly to changes in the load or environmental conditions;
- automatically regulate HVAC, lighting, energy consumption, and security;
- predict needs and optimise resources;
- ensure sustainability, energy efficiency, and comfort for users.

The implementation of these principles in practice can be traced in a number of landmark buildings constructed as part of comprehensive “smart” and sustainable urban projects. In particular, examples of adaptive architecture can be found in the South Korean smart city of Songdo (Songdo International Business District), which focuses on digital management of urban and construction infrastructure, and in the sustainable pilot-project Masdar City in Abu Dhabi (UAE), where the adaptability of buildings is achieved through the combination of passive climate strategies and intelligent control systems.

Below are examples of some key buildings in these cities as practical-use cases of adaptive architecture.

Posco Tower-Songdo is a 68-storey, 305-metre-high multifunctional skyscraper located in the Songdo International Business District. The building encompasses an office space, a hotel, service areas, and public facilities.

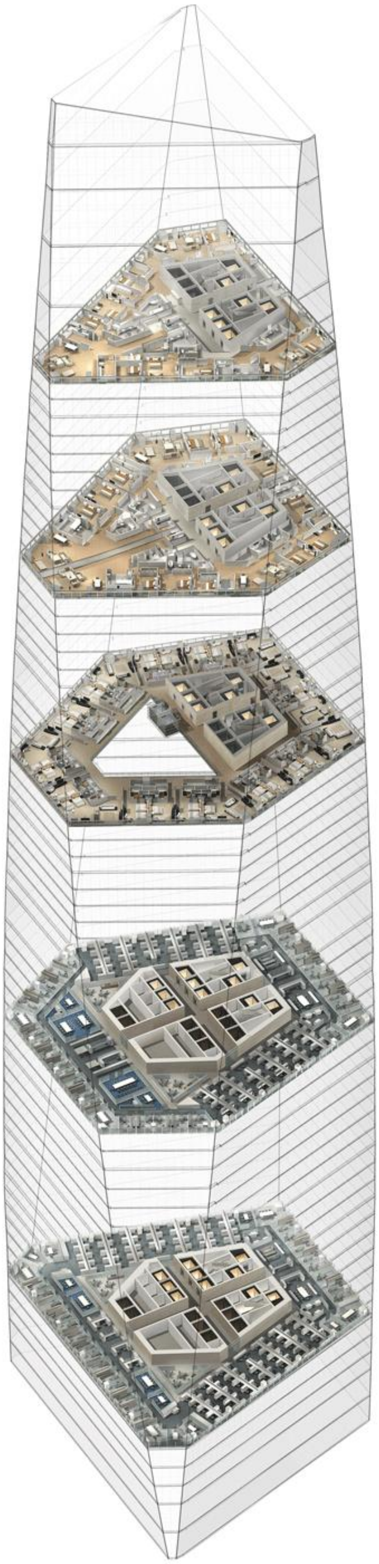


Fig. 5: Architectural and planning structure of Posco Tower-Songdo

The architectural and structural form of the tower was designed to adapt to extreme external impact, primarily wind exposure. In order to minimise the wind load capacity, the building has a three-dimensional external geometry, with a gradual transition from a trapezoidal base to a triangular shape at the top. This spatial solution allows for the redistribution of aerodynamic load and increases the overall stability of the high-rise structure, demonstrating the integration of the architectural form and engineering adaptability.

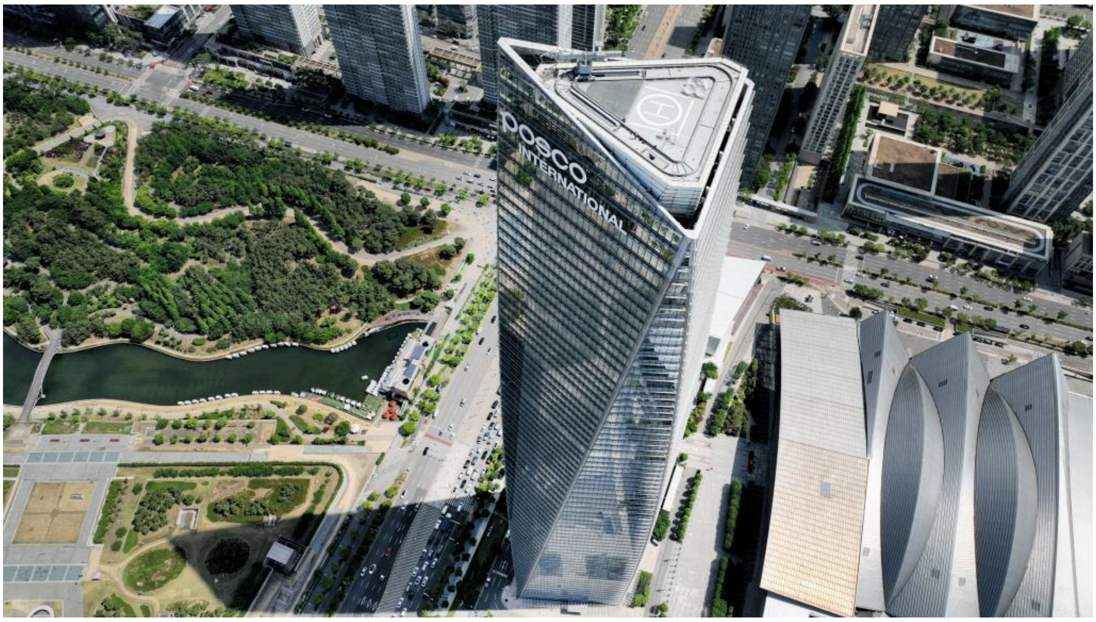


Fig. 6, 7: Posco Tower-Songdo

Posco Tower-Songdo’s maintenance services pay particular attention to safety and monitoring of the building’s operational condition. The tower is equipped with a global positioning system (GPS) that provides real-time measurements of vibration, displacement, and deformation of structures caused by wind, seismic activity, or other external factors. These data allow potential deviations to be identified in advance and preventive measures to be taken to maintain the structural integrity of the building. In addition, the structure is designed to withstand seismic impact measuring up to 7–8, which meets the high requirements for stability in earthquake-prone regions.

The functional adaptability of the building is complemented by a sophisticated emergency management system. The control centre, located on the first underground level, maintains centralised control of power supply, lighting, video surveillance, access control systems, and other engineering and utility services. The building structure provides for specialised shelters on the 30th and 60th floors, capable of safely accommodating up to 4,000 people in emergency situations such as fire.

Fig. 8: Emergency control centre located on the basement floor

The engineering systems of Posco Tower-Songdo are designed for adaptive and sustainable energy management. Like other buildings in New Songdo, the tower is connected to a highly efficient district cogeneration plant located in the immediate vicinity. Hot water for heating and cooling, with the use of absorption chillers, is generated by recovering waste heat produced in the power generation process. This approach allows the building’s energy modes to be flexibly adapted to current loads and ensure resource availability. It is estimated that the use of the cogeneration scheme reduces CO_2 emissions by approximately 6,000 tonnes per year compared to a traditional office tower using electric chillers and gas boilers [12].

Posco Tower-Songdo demonstrates the comprehensive realisation of the adaptive architecture principles, where the architectural form, structural solutions, monitoring systems, engineering infrastructure, and power strategies are combined into a single technological system. The building is capable of responding flexibly to changes in the external environment, operational loads, and potential risks, which makes it a representative example of sustainable and adaptive high-rise architecture in the structure of a smart city.

Songdo Convensia is a large congress and exhibition centre, one of the key public facilities in the smart city of Songdo. The building serves as an international exhibition and conference complex and was originally designed as a flexible, technologically equipped, and sustainable space capable of adapting to changing usage scenarios and intensive operational loads.

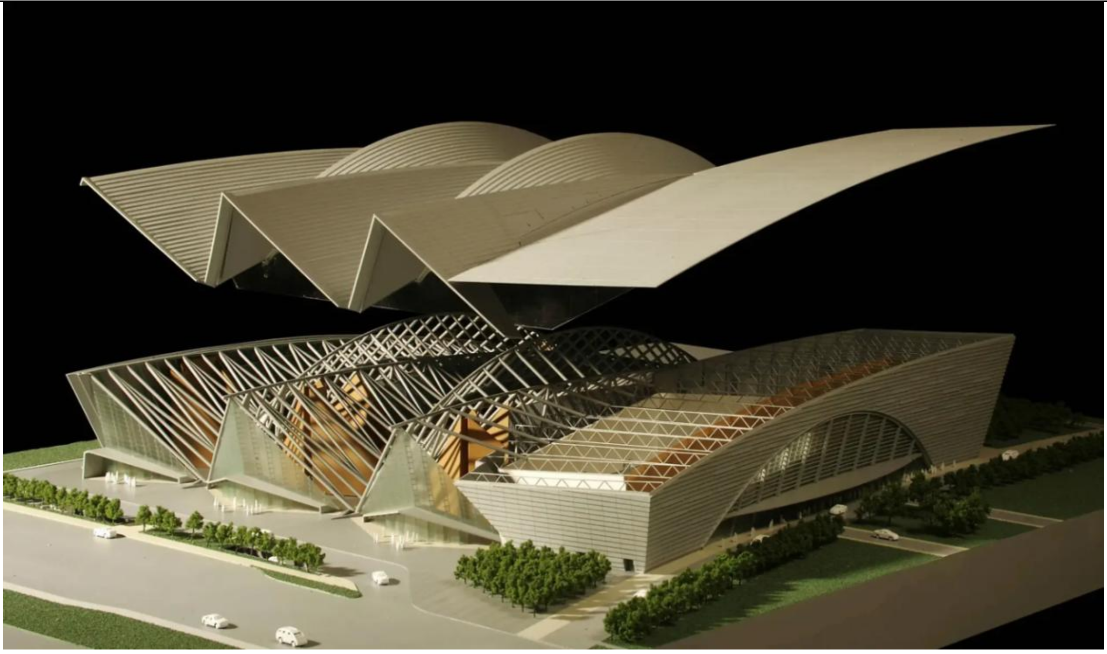


Fig. 9: Model of the Songdo Convensia exhibition centre

The architectural concept of Songdo Convensia is focused on the functional adaptability of interior spaces. The building includes one of the largest pillarless exhibition halls in Asia, which allows for a high capability for transformation of the layout structure depending on the format of the event – from international exhibitions and forums to concerts and public events. This spatial flexibility reduces the need for physical reconfiguration of the building and allows for efficient use of the facility throughout its life cycle.

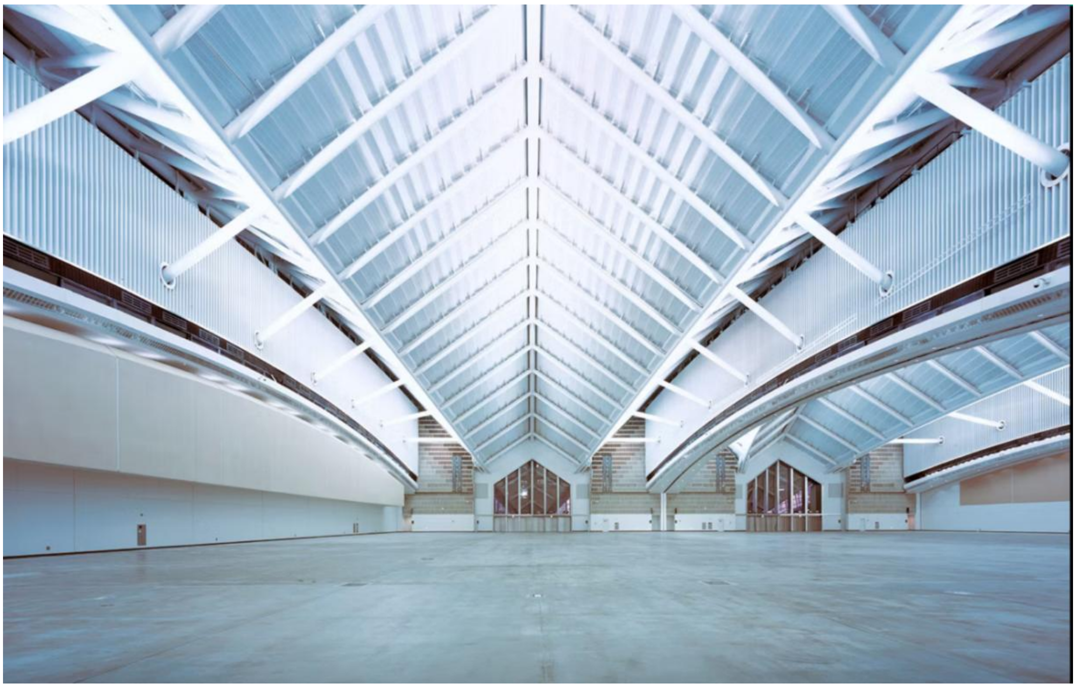


Fig. 10: Pillarless exhibition hall

Engineering and digital control systems play a significant role in shaping the adaptive architecture of Songdo Convensia. The building is LEED-certified, confirming the implementation of energy-efficient and environmentally-oriented solutions. The design and operation of the centre utilise systems for rational use of energy and water, as well as microclimate optimisation strategies aimed at reducing operating costs and environmental impact with regard to high visitor density [13].

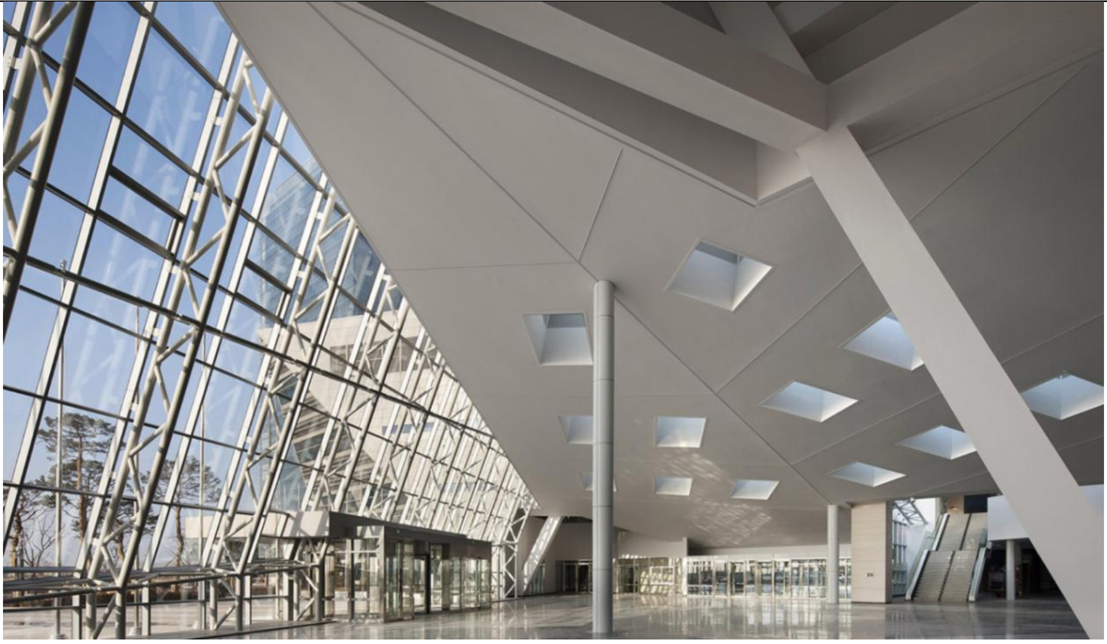
The technological adaptability of the building is supported through the integration of digital space management and user flow systems. Songdo Convensia uses wireless networks, RFID technologies, and access control systems that make it possible to track visitor flows, manage hall occupancy, and ensure event security.

The centre's engineering systems are designed to be adaptable to varying loads typical of exhibition and congress facilities. The ventilation and air conditioning systems are capable of operating in different modes with regard to the scale of the event, room crowding, and heat loads, which allows comfortable conditions to be maintained while reducing excess energy consumption. This approach reflects the adaptive control principles whereby the building responds not to predefined scenarios but to actual operating conditions.

G-Tower is a multifunctional high-rise building that serves as one of the key administrative and business facilities in the smart city of Songdo. The building houses offices of international organisations, government and private agencies, as well as public spaces, which determines the high requirements for functional flexibility, security, and technological status.

Fig. 11: G-Tower

The architectural and planning structure of G-Tower is designed to be adaptable to a variety of usage scenarios. The building combines office, public, and representative functions, which requires a flexible organisation of internal spaces and the possibility of their transformation without significant interference with the structural design. This approach allows the configuration of premises to be changed depending on the tenant mix, format of work, and operational needs, which is an important feature of adaptive architecture.



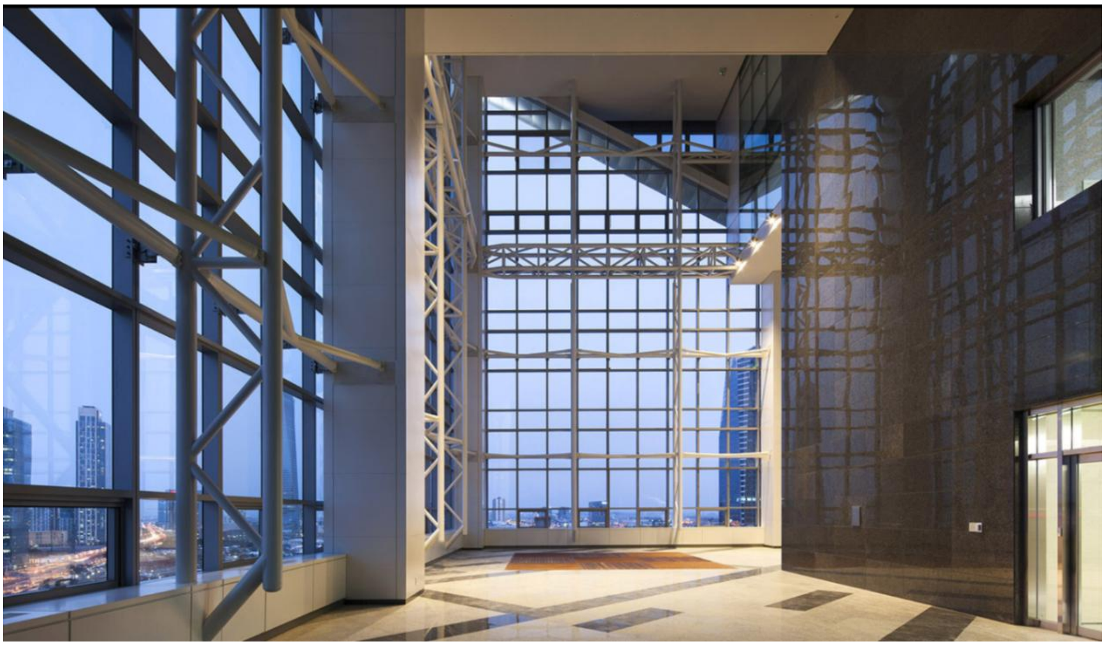


Fig. 12, 13: Interiors of G-Tower

The key element of G-Tower's technological adaptability is the Incheon Free Economic Zone Integrated Operation Centre (IFEZ) located on the 3rd and 4th floors of the building. The centre comprises a control room, an observation area, technical premises, and conference rooms with a total area of approximately 1,169.5 m². The centrepiece of the control facility is a dashboard comprising 85 modular screens (5 rows of 17 columns); above it is a 250 × 8,000 mm full-colour LED display designed to display emergency messages and operational information. The control room is equipped with 22 operator workstations and additional observation and analysis workbenches, ensuring round-the-clock monitoring and control of the smart city processes.

Fig. 14: Integrated control centre

The control centre’s operation emphasises the role of G-Tower as the core of Songdo’s digital infrastructure. The IFEZ Integrated Operation Centre houses the main hardware and software complexes that monitor the urban infrastructure, manage engineering systems, security, transport, and urban services. Thus, the building performs not only an administrative but also a strategic function, coordinating adaptive processes throughout the Songdo district [14, p. 18].

The centralised video surveillance, access control, and engineering network monitoring systems within the IFEZ are integrated into a single management platform that receives data from more than 1,000 cameras. This is effectuated round the clock by 51 operators, including 28 CCTV monitoring specialists and 4 emergency response operators, which ensures rapid processing of events and transmission of critical information to the relevant services. The average CCTV operator’s workload covers about 140 cameras per person [15].

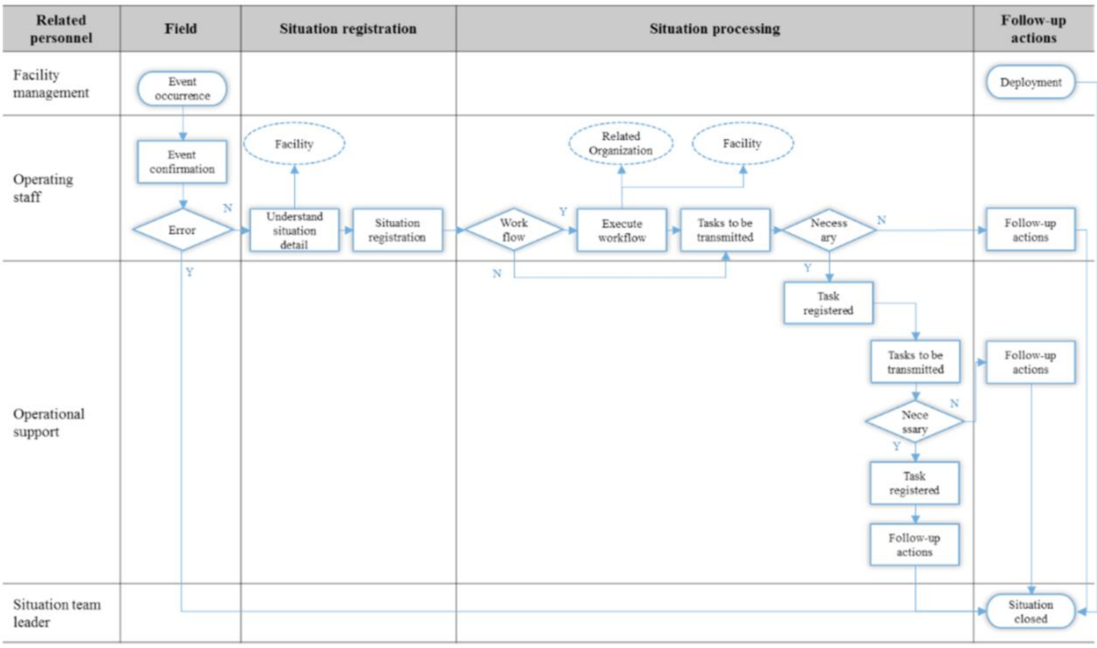


Fig. 15: Emergency situation management chart [15].

The above chart shows the full cycle of emergency management: from recording and confirmation of an emergency event by an operator to registration of the incident, launch of regulated response scenarios, distribution of tasks between the services, and subsequent monitoring of performance. The process involves a multi-level check of the need for additional actions, and ends with an official closure of the case by the response manager.

Siemens Middle East Headquarters in *Masdar City*, Abu Dhabi (UAE), is one of the earliest and most illustrative examples of realising the principles of sustainable and adaptive office architecture in the conditions of extreme desert climate. The building was designed by the British architectural firm *Sheppard Robson* and commissioned in 2013.

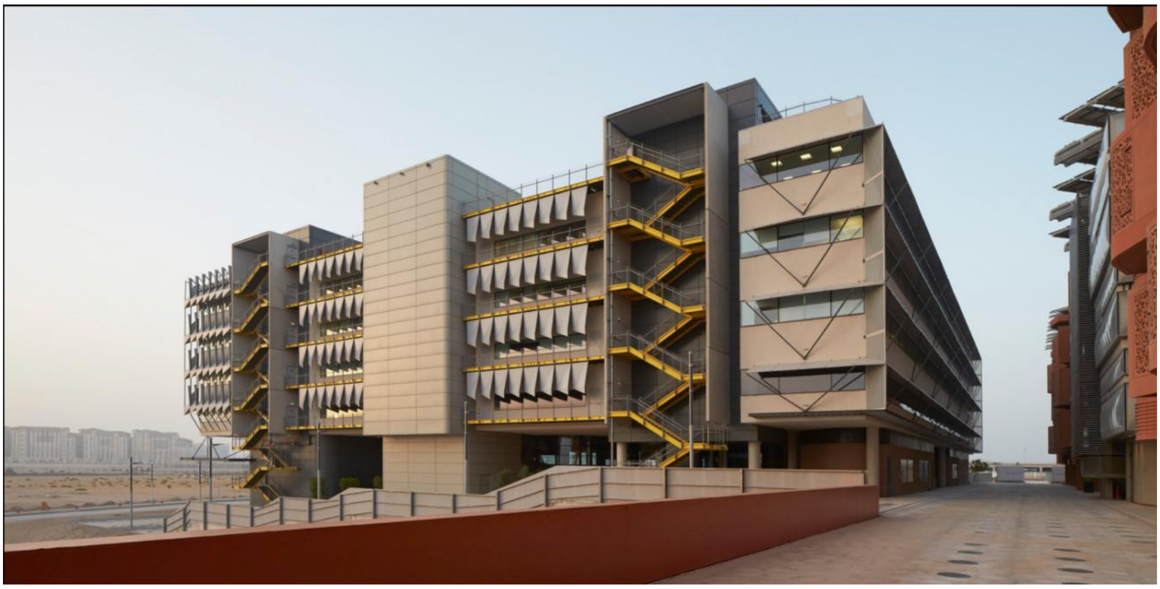


Fig. 16: Siemens Middle East Headquarters

This facility was designed to reduce energy consumption by 46% compared to the ASHRAE 90.1-2007 baseline. This was achieved through the improved design of the building envelopment and the use of highly efficient HVAC systems. In addition, the project implements effective solutions for the use of natural lighting, as well as a complex of passive and active design strategies. At the same time, the cost of the building did not exceed the level comparable to similar facilities in the region [16, p. 105].

Architecturally, the *Siemens HQ* project was based on a complex combination of traditional climate strategies and parametric analysis: the formation of a compact, optimised structure made it possible to reduce material consumption and minimise embodied carbon effects.

The building's outline is designed as a "box within a box", where:

- **The internal, highly insulated and airproof façade** reduces heat transfer through the building envelopment;
- **The external lightweight aluminium sun protection system** minimises direct solar gain while increasing diffused light penetration and visual contact with the outside

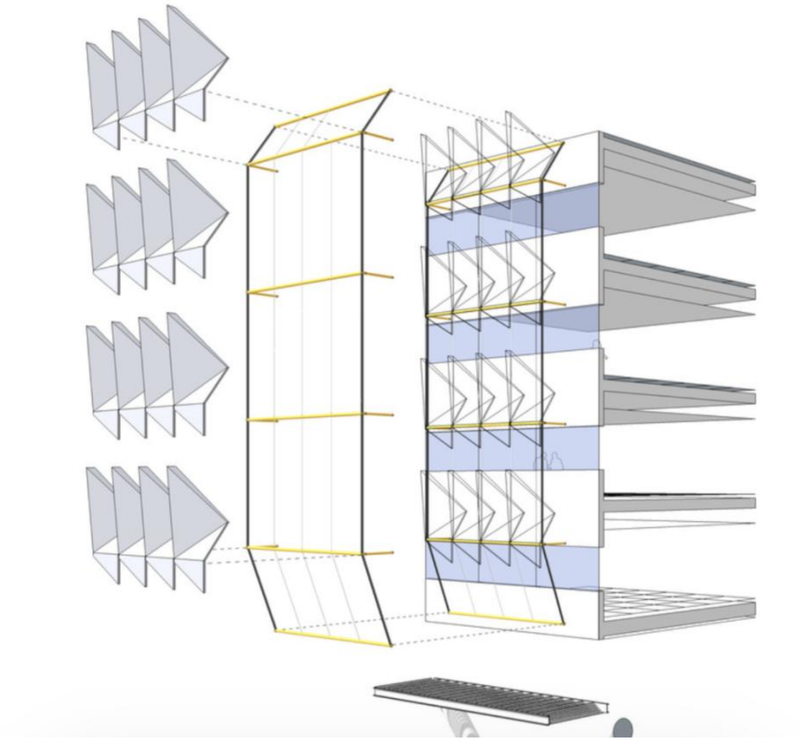


Fig. 17: Structural chart of the building façade

This solution of the façade lessens the need for active cooling, reducing the load on engineering systems and ensuring high energy efficiency in the conditions of the hot climate.

According to the modelling and computed simulation results, the building's annual energy consumption is 109.5 kWh/m² (AECOM, design notes), which is significantly lower than the "standard practice" benchmark for commercial buildings in Abu Dhabi, which is 333 kWh/m² [16, p. 109].

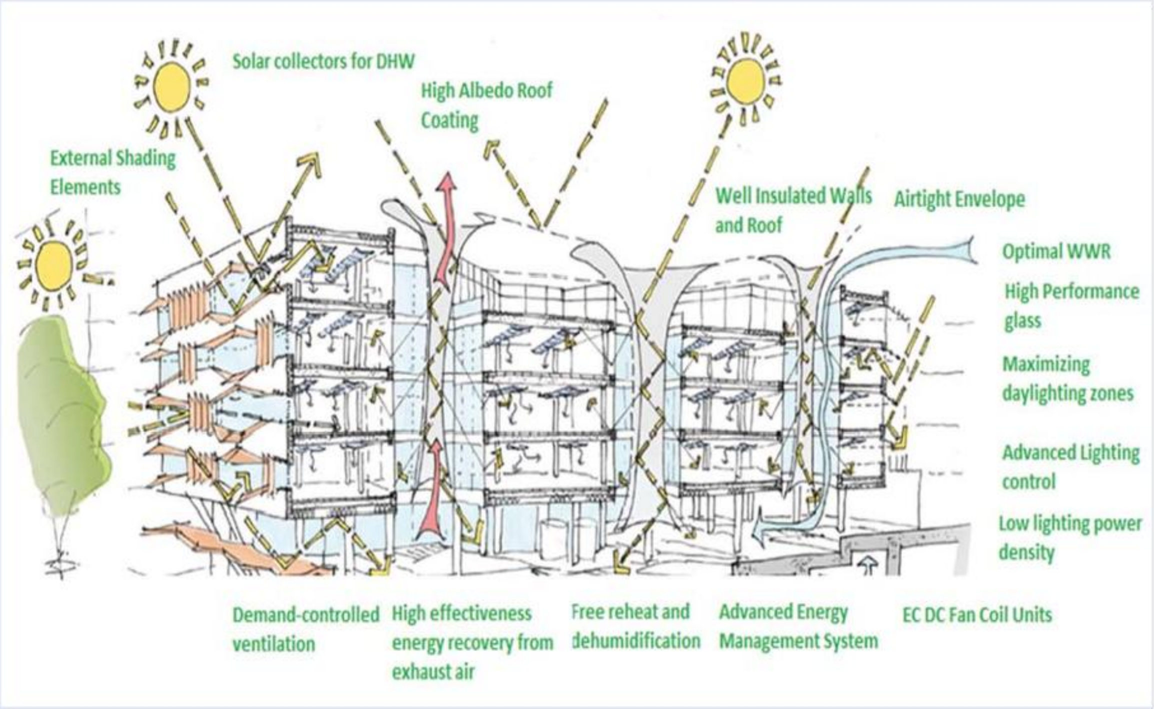


Fig. 18: Key design strategies applied in the Siemens building [16]

In addition to passive architecture strategies, the Building Management System, along with the integrated *Siemens* engineering technologies, enable dynamic matching of energy consumption with the actual demand and increased operational efficiency, further reducing operating costs and carbon emissions [17].

Despite the dominance of passive climate strategies, the operational adaptability of the Siemens Middle East Headquarters in Masdar City is enhanced by digital control systems that comply with the IoT–BMS–Cloud architecture. It is worth noting that the building is run, in terms of application and service maintenance, by the MindSphere cloud IoT platform developed by Siemens to create digital solutions for industry and smart city infrastructure [18]. MindSphere collects data from sensors and controllers, organises their storage in the cloud, performs analytics, and generates reports and forecasts for the operation of the equipment. In addition, the application uses machine learning and AI for predictive maintenance and process optimisation, integrates with BMS, ERP, and other digital platforms, and provides remote access for developers and engineers around the world [19].

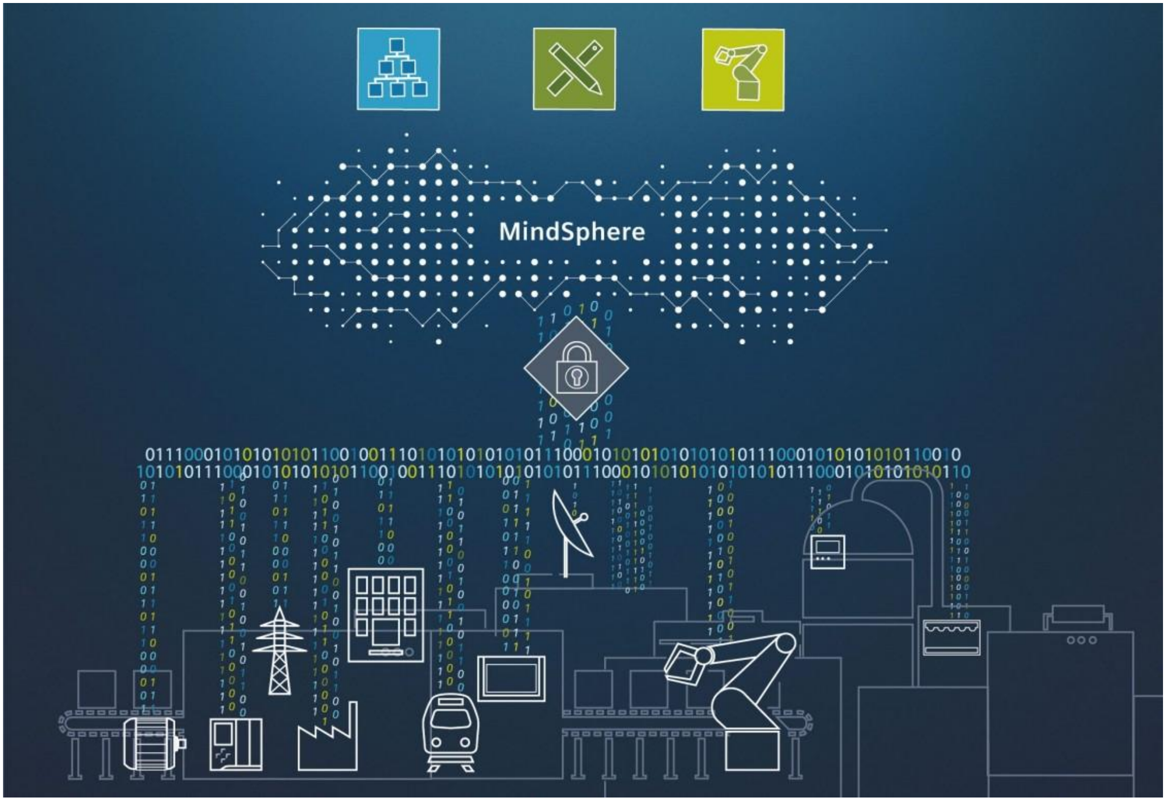


Fig. 19: Schematic representation of MindSphere operation

For the proper digital operation of the building, Siemens has enacted a range of fully integrated building technologies, including the advanced building management system (BMS). The system makes it possible to improve energy efficiency and optimise operating cost savings. The building is equipped with the latest Siemens security systems, as well as fire alarm and gas fire extinguishing technologies, lighting control and management systems [20].

Cloud platforms provide storage and analytical processing of operational data, allowing for the optimisation of cooling, lighting, and energy consumption modes, with regard to the factual load and climatic conditions.

Masdar City Headquarters is one of the most ambitious projects of the smart Masdar City, designed by Adrian Smith + Gordon Gill Architecture studio.

Fig. 20: Masdar City Headquarters render chart

Despite not having been implemented, the project is considered an example of integrated application of BIM technologies at the conceptual and detailed design stages, where information modelling was used to coordinate architectural, structural, and engineering solutions and to develop sustainable design parameters.

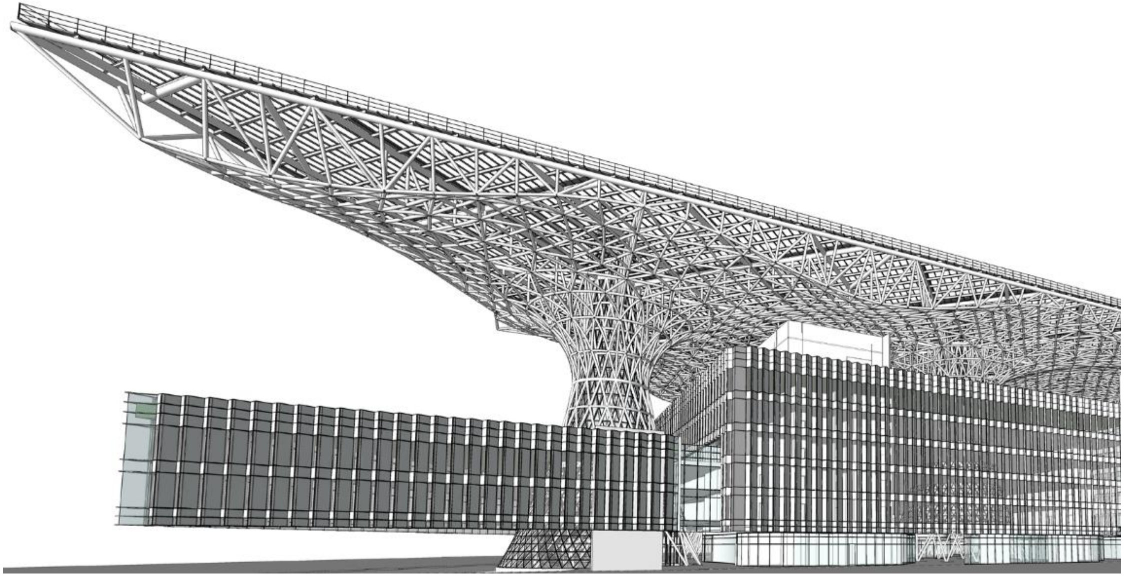


Fig. 21: BIM chart [21].

At Masdar City Headquarters, an integrated set of specialised BIM software was used for information modelling: Autodesk Revit Architecture, Revit Structure and Revit MEP, as well as analysis and coordination tools – Autodesk Ecotect Analysis and Navisworks Manage. The project team noted that 100% of the operational documentation for the engineering systems was directly generated on the basis of the Revit MEP model (more than 800 drawing sheets), which indicates the extensive use of the BIM model at the operational documentation stage. In addition, Navisworks Manage was used to identify discrepancies between architectural, structural, and engineering systems, while the BIM approach allowed the participants to simultaneously analyse design solutions and make quick decisions on sustainability and cost based on the integrated model [21].

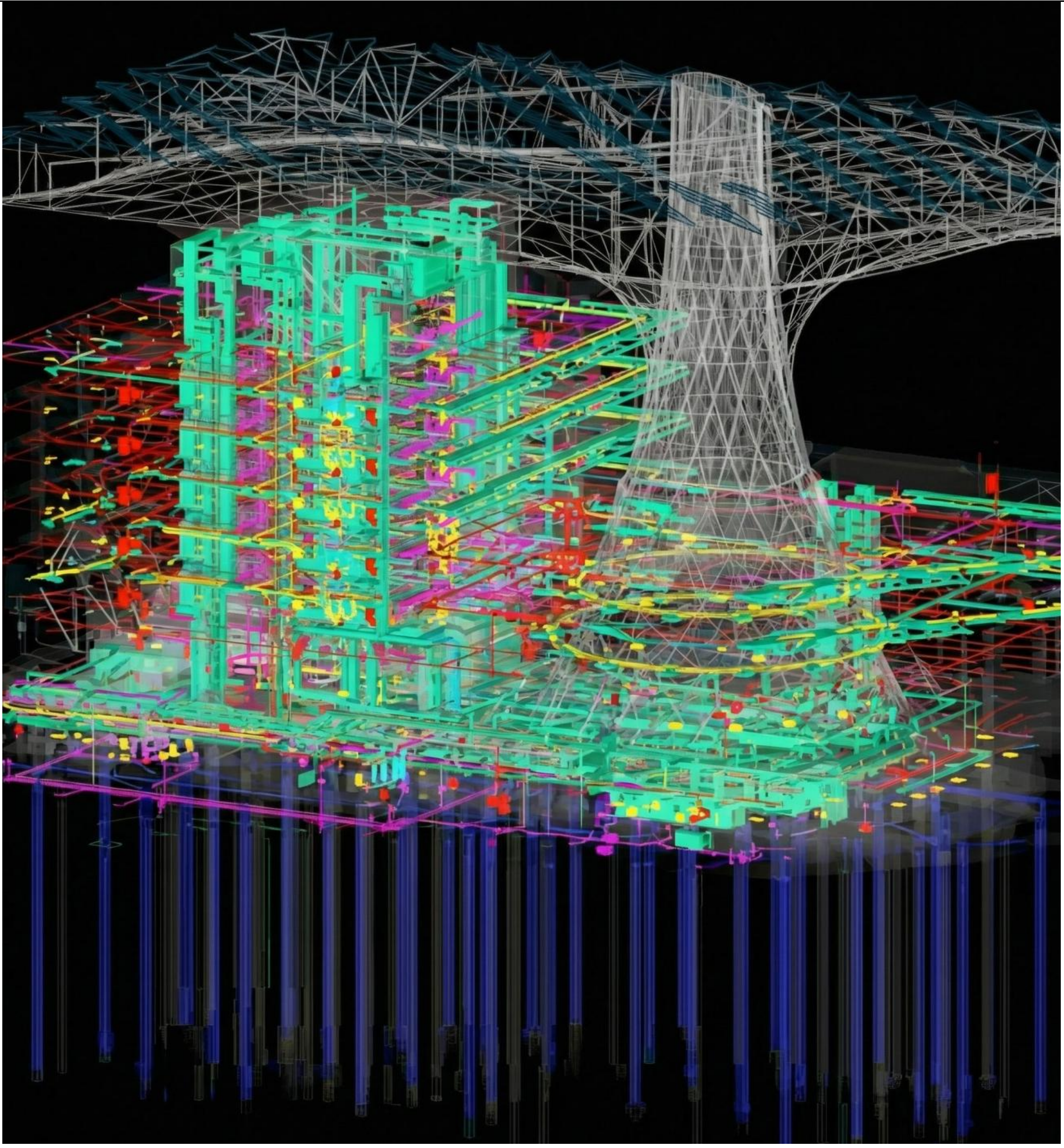
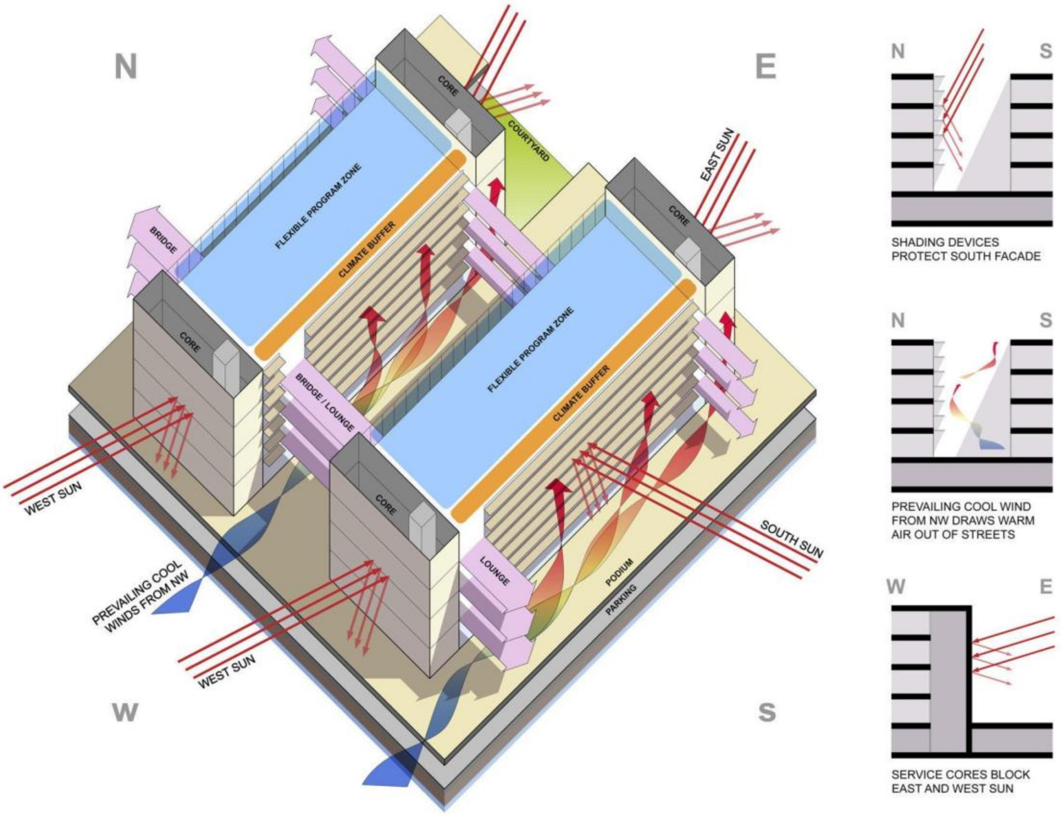


Fig. 22: Colour coding of mechanical, electrical and plumbing (MEP) systems and fire protection facilities [21]

Khalifa University represents a complex of educational and research buildings that form the academic core of Masdar City. The architecture of the complex is based on the principles of climate adaptation and interpretation of traditional Middle Eastern urban development styles.

Fig. 23: Khalifa University building complex

The buildings are grouped around shaded courtyards, which help to maintain natural ventilation and a cooler microclimate. Narrow passageways, deep façade recesses and screening elements (mashrabiya) reduce the impact of direct solar radiation and help to lower indoor temperatures.



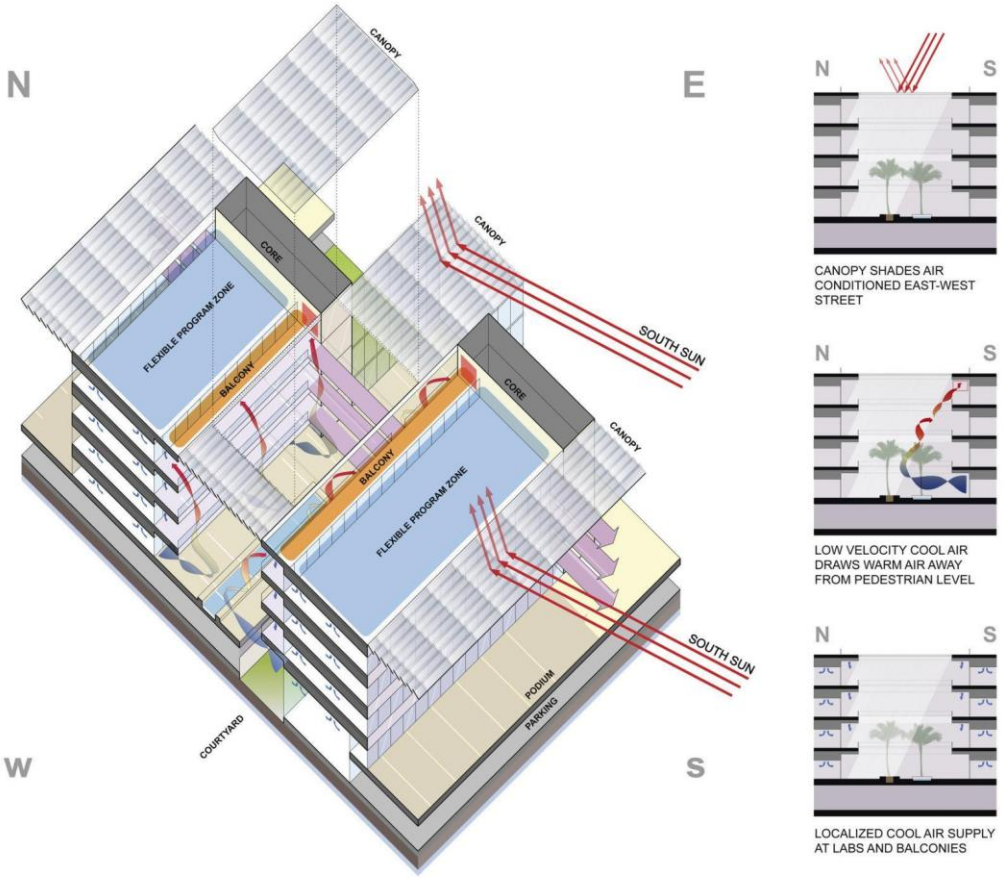


Fig. 24, 25:Climate adaptability chart for Khalifa University buildings

The engineering systems of the university are integrated with monitoring and control systems, allowing cooling, lighting, and ventilation modes to be adapted to the time of day, season, and user presence. This approach ensures sustainability and energy efficiency, favouring intensive educational and research use.

Thus, the examples of the above facilities let one argue that adaptive architecture represents a digital/physical adaptable system in which IoT provides sensory perception of the operating parameters; BIM forms the spatial and functional context, whereas cloud technologies are in charge of intelligent data processing and operational process management at the level of the entire building infrastructure.

The table of adaptive architecture components shows how IoT, BIM, and cloud technologies are combined to enable dynamic smart building management, including data collection, analytical processing, and automated control of engineering systems.

Table 4: Adaptability components and technologies used in smart buildings

Component	**Functions and purpose**	**Note/technology**
IoT sensors	Collecting data on temperature, humidity, lighting, movement, energy consumption	Includes RFID tags, energy meters, motion and illumination sensors
BIM (digital twin)	Structured representation of the building's physical and functional components; contextual model	Takes into account the layout of premises, air volume, zoning, and other spatial characteristics
Cloud platform	Scalable data processing, history storage, AI algorithmic operation, remote monitoring	Ensures IoT and BIM integration, big data analytical processing
HVAC control system	Automated control of temperature, ventilation, and air conditioning	Uses IoT data and AI forecasts
Lighting control system	Dynamic adjustment of light intensity depending on people's presence and illumination level	Reduces energy consumption, enhances comfort

Security systems	Video surveillance, motion sensors, fire safety systems; automatic response to incidents	Integrated with IoT for round-the-clock monitoring
AI level / analytics	Demand forecasting, resource optimisation, anomaly detection	Uses IoT and BIM data for real-time decision-making
Communication infrastructure	Data transfer between sensors, BIM and the cloud	Wi-Fi, LoRa, 5G, security protocols
Energy efficiency and sustainability	Automatic optimisation of energy consumption, adaptation to changing conditions	Uses load forecasting and dynamic system regulation

However, despite these integrated solutions, recent 2023–2025 studies identify a number of significant challenges that constrain the effectiveness and scalability of adaptive systems.

Firstly, interoperability and standardisation remain key challenges: the heterogeneous nature of sensors, actuators, and communication protocols complicates the integration of the components shown in the table and the construction of a unified architecture [22].

Secondly, data privacy and security become critical with the widespread connection of IoT devices and the transfer of information to the cloud. Even with AI analytics and BIM models, there is a risk of leaks, hacks, and unauthorised access [23].

The third problem is network reliability and delays: distributed computing at the network edge and in the cloud can experience fluctuations in delays and interruptions, which limits the responsiveness of the HVAC, lighting, and security systems described in the table [24].

In addition, the limited resources of IoT devices – memory, computing power, and energy capacity – impose constraints on the execution of complex adaptive algorithms and processing of large data streams in real time [25].

Finally, scalability remains a challenge as the number of devices increases: load balancing between the edge and the cloud, as well as managing a large number of sensors and actuators, requires additional solutions to ensure stable operation of the entire architecture [26].

The table below summarises the key problems of implementing adaptive architecture and the ways to address them. The table demonstrates how interdisciplinary approaches, open standards, educational programmes, and strategic management can directly mitigate the identified challenges, providing a more sustainable and scalable architectural system.

Table 5: Description of the main problems of adaptive architecture, and proposed solutions to handle these challenges

Problem	**Description**	**Solutions/Technologies**
Interoperability and standardisation	The heterogeneity of sensors, actuators, and communication protocols complicates the integration of components	Use of open standards (IFC, COBie, MQTT, CoAP); development of plugins and APIs; integration via cloud platforms; creation of international standards for sensors and devices [22]
Data privacy and security	En-masse connection of IoT devices and transfer of data to the cloud create a risk of leaks and hacks	Federated learning; blockchain; cryptography (encryption, access control, digital signatures); multi-level security system [9, 10, 11, 23].
Network reliability and delays	Distributed computing faces fluctuations in delays and interruptions, which limits system responsiveness	Edge computing; data quantisation and compression; backup transmission channels; load balancing between the edge and the cloud [9, 11, 24]
Limited resources of IoT devices	Memory, computing power, and energy capacity constrain the execution of complex algorithms	Optimisation of AI algorithms for small devices; clustering of devices and data; use of energy-efficient sensors and adaptive operating mode [9, 11, 25]
Scalability	Increasing the number of devices complicates the control of sensors and actuating systems	Dynamic load distribution; modular architecture for easy expansion; cloud platforms with horizontal scaling [26]

The table clearly demonstrates the relationship between the main barriers to the implementation of adaptive architecture and possible strategies for overcoming them. It emphasises that the effective integration of IoT, BIM, and cloud technologies requires a comprehensive approach that includes technical solutions, educational programmes, development of standards, and strategic change management. The application of these methods can increase component compatibility, ensure data security, improve scalability, and accelerate the implementation of innovative technologies in smart buildings.

Conclusion

- The concept of a smart city is evolving from a simple technological buildup of the urban environment to the integration of sustainable, intelligent, and user-oriented systems. Architecture is becoming a central element bringing together digital technologies, physical infrastructure, and social processes. It acts as a spatial interface enabling interaction between people, data, and engineering systems, which is critical for the sustainable development of cities.
- The IoT, sensor networks, AI, digital twins, and cloud platforms form the basis for the functioning of a smart urban environment. These technologies enable buildings to “sense” the environment, predict user needs, and automatically control engineering systems, improving energy efficiency, safety, and comfort.
- BIM provides a structured and contextual representation of buildings throughout their entire life cycle. The use of digital models allows for the integration of IoT data and cloud computing for monitoring, analysing, and optimising building operation. However, the implementation of BIM faces challenges such as interoperability issues, limited application in the residential sector, high start-up costs, and staff competency gaps.
- IoT devices and sensor modules provide continuous collection of data on the condition of the building and user behaviour. AI algorithms analyse these data, predict the load, and automatically control HVAC, lighting, and security systems. The introduction of IoT and AI improves operational efficiency and energy performance, but is attended by risks related to privacy, cybersecurity, limited scalability, and dependence on cloud services.
- Federated learning allows AI models to be trained on local devices without transferring data to the cloud, which reduces the risk of information leaks and lowers energy consumption. Blockchain integration ensures data protection, immutability of records, and decentralised management. Joint use of these technologies forms a multi-level smart-building management architecture capable of addressing security issues, scalability, and energy efficiency problems.
- Adaptive architecture brings together the capabilities of IoT, BIM, and the cloud to create a dynamic, self-adjusting building management system. It allows for rapid response to changes in the load, environmental conditions, and user behaviour, forecasting needs, optimising resources, and ensuring comfort and sustainability. The adaptive architecture components include sensor and actuator systems, BIM models, cloud platforms, the AI layer, and communication infrastructure.
- Recent studies highlight the key challenges: device interoperability, standardisation, data privacy and security, network reliability, limited IoT device resources, and architecture scalability. These problems require a comprehensive approach, which includes developing educational programmes and implementing open standards, pilot projects, strategic change management, and legal regulation.

Summary

The architecture of a smart city represents a multi-level integration of technologies, engineering systems, and social processes, where buildings function as active intelligent units. The integrated use of IoT, BIM, cloud technologies, AI, federated learning, and blockchain enables dynamic, autonomous, and energy-efficient management of the urban environment. However, the effectiveness of such systems directly depends on solving the problems of compatibility, security, staff competencies, and regulatory control.

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