

## APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES AT ALL STAGES OF THE BUILDING LIFE CYCLE

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**Abstract:** Artificial Intelligence (AI) is increasingly being integrated into the architecture, engineering, and construction (AEC) industry, covering all stages of a building's life cycle — from conceptual design and planning to construction, operation, and even deconstruction. This review summarizes current approaches to the application of AI technologies across these phases. It examines tools for generative design, machine learning algorithms for construction optimization, and AI-based building management systems. The analysis highlights that AI enhances building efficiency and sustainability by optimizing energy consumption, reducing construction waste, and enabling predictive maintenance. Key benefits of AI adoption are identified, including process acceleration, cost reduction, and improved safety, along with challenges such as the shortage of skilled professionals, data security issues, and lack of regulatory standards. The article concludes by emphasizing the urgency of accelerating the digital transformation of the construction sector — particularly through the development of national BIM-related standards in Uzbekistan — to fully realize the potential of AI at all stages of the building life cycle.

**Keywords:** artificial intelligence; building life cycle; BIM; design; construction; operation; digital twin; automation; sustainable building

### Introduction

The construction industry has long been characterized by labor-intensive processes and significant resource losses. According to estimates, buildings account for up to 40% of global energy consumption and nearly 30% of CO<sub>2</sub> emissions. Furthermore, approximately 11–15% of construction materials are lost during the building process, underscoring the inefficiency of current practices. In this context, the adoption of advanced digital technologies becomes critically important. Among the most promising innovations is Artificial Intelligence (AI), a set of machine learning, data analytics, and automation techniques capable of revolutionizing the design, construction, and operation of buildings.

In recent years, there has been a rapid increase in interest in AI across the fields of architecture and construction. Globally, major AEC firms are investing in research and pilot projects to implement AI-based solutions. According to a report by Autodesk, 76% of organizations in the architecture, engineering, and construction sectors plan to increase their investments in AI within the next three years. Successful examples already demonstrate the economic impact of AI adoption. For instance, in a residential project in California, the use of Autodesk Forma — an AI-driven design platform — reduced the time required to develop an architectural concept from two weeks to just six hours, while simultaneously lowering both the projected cost and carbon footprint of the project by nearly 50%. Such outcomes illustrate the transformative potential of AI technologies.

At the same time, analysts note that the application of AI is unevenly distributed across the stages of a building's life cycle. The majority of current implementations are concentrated at the operation phase

(building management), whereas the design and construction stages remain less explored in terms of AI integration [1]. This disparity is attributed to both technological barriers and the lack of a regulatory framework. In particular, Uzbekistan currently lacks officially adopted national standards for Building Information Modeling (BIM) and formal regulations governing the use of AI in the construction sector. The development and approval of such standards (known as SHNK – urban planning norms and rules) is highly urgent to ensure the national industry does not lag behind in the digital transformation process.

The objective of this study is to provide a comprehensive overview of current AI technologies and their application at key stages of the building life cycle: design, construction, and operation. The following sections present a review of the relevant literature, describe the research methodology, summarize findings by life cycle stage, discuss key advantages and limitations, and draw conclusions on the prospects for AI adoption in the construction sector.

### Literature Review

In recent years, both academic and industry literature have increasingly explored the potential of artificial intelligence (AI) at various stages of the building life cycle. A review of publications reveals that researchers have high expectations for AI in improving the sustainability and efficiency of buildings. For instance, a systematic review by Adewale et al. [1] synthesized more than 100 studies and concluded that AI can significantly enhance building sustainability by optimizing energy consumption, enabling predictive maintenance of equipment, and supporting data-driven design decisions. It is noted that advanced machine learning algorithms, when combined with digital twin technologies, provide real-time insights for building operations and for reducing environmental impact [2].

Practical aspects of AI implementation are also widely discussed in professional and engineering domains. Consultant engineer Robert Knoedler [3] describes the use of AI “throughout the entire building life cycle,” highlighting how architects, contractors, and facility managers are already leveraging AI-based tools to enhance performance. Specifically, architects are applying generative algorithms in conceptual design; construction firms use computer vision for real-time site monitoring; and building operators are adopting intelligent building management systems to reduce energy consumption. According to Autodesk [4], the integration of AI with Building Information Modelling (BIM) and Internet of Things (IoT) technologies spans all stages of the project — from automated clash detection in design models to construction schedule optimization and predictive equipment failure analytics during operation [4]. This integrated approach, as these studies suggest, contributes to making buildings “smarter, more efficient, and more adaptive” to future needs [5].

At the same time, several authors highlight notable research gaps. First, there is insufficient attention to the decommissioning phase of buildings — although AI could support material recovery and demolition planning, few studies address this stage. Second, there is a shortage of skilled personnel and methodological capacity for AI implementation: the global construction sector faces a deficit of professionals with data science and machine learning expertise, which hampers further research and deployment. Third, regulatory challenges remain unresolved — there is a lack of unified data exchange protocols and quality standards for AI systems, which complicates the comparison of results across projects. These issues must be addressed, including through the development of regulatory frameworks

— in the context of Uzbekistan, by accelerating the adoption of national technical standards for BIM and digital building lifecycle management.

Thus, the literature confirms the significant potential of AI across all stages of the building life cycle, while simultaneously identifying the need for further empirical research and institutional support. The next section outlines the research methodology and presents results structured by life cycle stage.

## Methodology

This study was conducted as a narrative literature review. It involved the collection and analysis of scientific publications from 2018 to 2025, as well as industry reports and articles focused on the use of artificial intelligence (AI) in the construction sector. Emphasis was placed on international sources — including peer-reviewed journals, conference proceedings, and corporate white papers — to reflect cutting-edge global practices. The selection criteria included studies explicitly addressing the application of AI at the design, construction, and operation stages of buildings. In total, approximately 30 sources were reviewed, with the most illustrative examples and datasets incorporated into the analysis.

The gathered material was synthesized around key thematic areas: generative design, AI in construction management, intelligent operation systems, and related domains. This approach allowed the authors to construct a comprehensive picture of the current status and future prospects for AI integration throughout all stages of the building life cycle.

## Results and Discussion

Figure 1 illustrates how artificial intelligence technologies are applied at different stages of the building life cycle — beginning with the design phase (generative and parametric design), continuing through the construction phase (process optimization and safety monitoring), and culminating in the operation phase (energy management and predictive maintenance). Each stage is associated with specific AI tools and techniques; together, they form a continuous cycle of performance and quality improvements throughout the life of a building. The following sections provide a detailed examination

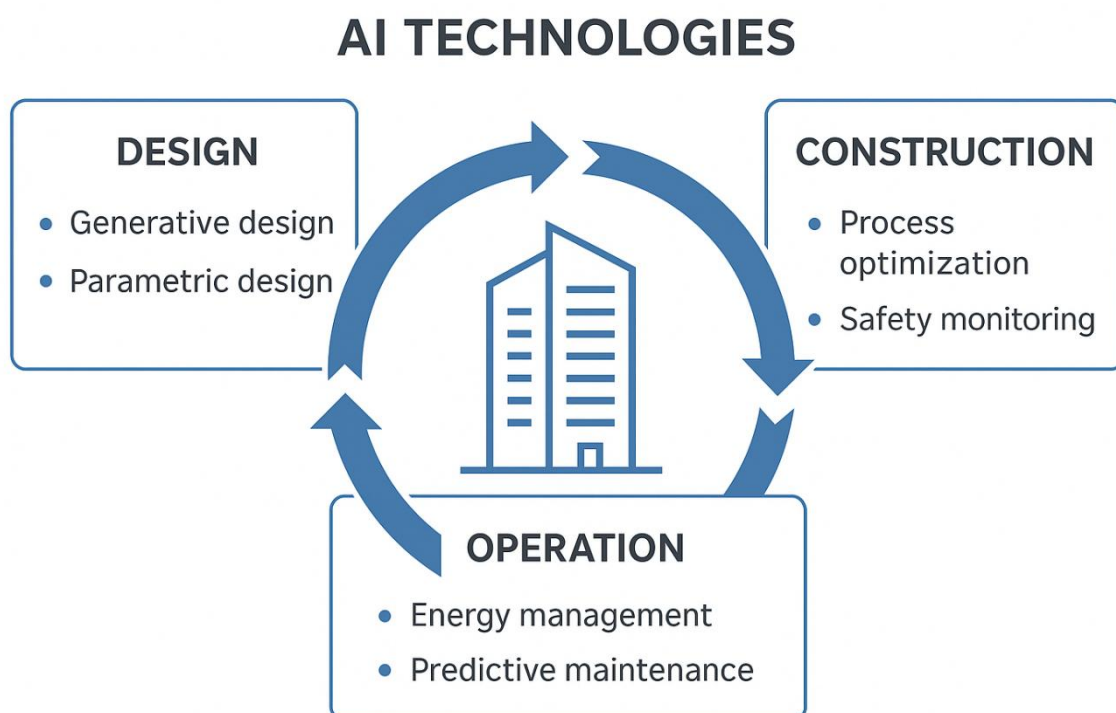


Figure 1. Integration of artificial intelligence tools at key stages of the building life cycle — design, construction, and operation — illustrating the continuous optimization of building performance.

of the three core stages and the primary directions of AI implementation within each.

### **AI in the Design Stage**

The architectural design stage defines the foundational quality of a building, and it is at this point that artificial intelligence (AI) opens new opportunities for optimizing decision-making. One of the most rapidly evolving areas is generative design — the use of algorithms to automatically generate project alternatives based on predefined parameters and constraints. Modern AI-powered tools enable architects to instantly create dozens or even hundreds of design variants, taking into account building codes, spatial logic, and environmental factors. For example, algorithms based on generative adversarial networks (GANs) can produce floor plan sketches aligned with solar access, ventilation patterns, and space zoning requirements. These systems significantly accelerate the early conceptual stages of design, enabling analysis in hours rather than the weeks traditionally required through manual iteration.

Beyond form generation, AI also supports evidence-based decision-making. Machine learning models are increasingly integrated into Building Information Modelling (BIM) systems for structural optimization. Engineers use AI-powered strength analysis tools to evaluate thousands of combinations of materials and cross-sections in search of cost-effective and structurally sound solutions. This results in optimized structures with minimal redundancy and reduced material waste. HVAC engineers apply ML models for energy consumption simulations — by combining climate data, equipment parameters, and space usage profiles, AI enables more accurate load calculations and the selection of energy-efficient configurations. Similar approaches are used for early-stage sustainability assessments: AI-assisted platforms such as Autodesk Forma immediately calculate a project's carbon footprint and suggest design alternatives to reduce environmental impact even at the conceptual phase [4].

AI is also increasingly used to automate routine design tasks. For instance, drawing and document classification algorithms can automatically check compliance with regulations and generate revision comments, saving valuable time for professionals. Architects have begun using generative language models such as ChatGPT to draft narratives, technical justifications, and explanatory notes — improving documentation quality and streamlining project preparation. In addition, computer vision tools can recognize objects in photographs of existing buildings and reconstruct 3D models from images, a method widely used in renovation projects to rapidly digitize legacy structures for redesign purposes.

In summary, during the design stage, AI acts as an "intelligent assistant" to architects and engineers. It generates creative ideas, suggests optimizations, and handles repetitive tasks, enabling professionals to focus on higher-level, creative challenges. In practice, the adoption of AI at this stage already leads to reduced workload and improved project quality. As noted by Autodesk, integrating AI tools into the BIM environment accelerates design workflows and decreases error rates by automatically detecting clashes and inconsistencies before construction begins [4]. Thus, AI in design contributes to the creation of more deliberate, efficient, and sustainable buildings from the very beginning of their life cycle.

## AI in the Construction Stage

During the construction phase, artificial intelligence (AI) is applied to increase productivity, enhance site monitoring and safety, and optimize scheduling and cost management. One of the most critical areas is the use of predictive and planning algorithms for project management. Specialized AI software analyses project data, construction schedules, and large volumes of historical data from similar projects to optimize current timelines. Machine learning models help forecast potential delays or budget overruns by identifying bottlenecks early in the planning phase. For example, AI algorithms can predict that a specific sequence of tasks may cause crew conflicts in the same zone and suggest a revised schedule. As a result, project managers are equipped with tools for proactive management — enabling them to identify and mitigate issues before they escalate.

Another essential application of AI is real-time construction site monitoring. This is made possible through the integration of computer vision and IoT sensor technologies. Cameras — including those mounted on drones, cranes, or even workers' helmets — stream video feeds that are analyzed by neural networks. These systems automatically track progress by comparing real-time imagery with BIM models or previous scans, detecting deviations such as installation errors, schedule delays, or unexpected obstacles. For instance, the OpenSpace platform uses 360° cameras to scan all site areas daily, and AI identifies which parts of the building are completed and which remain under construction. This enables site supervisors and clients to remotely access up-to-date visual insights and make informed decisions more quickly.

Particular attention is paid to health and safety compliance, where AI significantly improves hazard detection and response. Real-time computer vision systems analyze video feeds to identify risky behaviors: workers standing too close to danger zones, not wearing helmets or harnesses, or construction machinery approaching personnel. Upon detecting such risks, the system immediately sends alerts to the safety officer, enabling rapid intervention. Additionally, AI can analyze the BIM model and construction plan to highlight high-risk zones — such as areas prone to falls or structural overload — helping to pre-plan protective barriers, signage, and workflows to minimize accident likelihood. In practice, sites that adopt AI-based monitoring tools already report reductions in workplace injuries.

Another emerging direction is robotics and automation powered by AI. Physical robots equipped with AI algorithms are now performing specific construction tasks, particularly those that are hazardous or repetitive for human workers. Around the world, prototype bricklaying robots and robotic 3D concrete printers are being tested and deployed. AI-based controllers manage these machines in real time, adjusting their operations based on sensor and camera feedback to ensure precision. This leads to faster task execution and minimizes human error. For example, automated bricklaying can significantly accelerate wall construction while eliminating the risks associated with repetitive strain injuries in manual labor. Beyond robotics, construction sites also employ AI-guided drones for inspecting hard-to-reach areas — such as rooftops or high-rise structures. The drones capture imagery that neural networks analyze for defects, misalignments, or safety issues. Research suggests that robotics and AI-driven automation can reduce construction waste and costs while enhancing build quality through strict adherence to specifications.

In summary, during the construction stage, AI functions as both a “smart manager” and an “inspector.” It optimizes schedules, monitors progress and safety, and increasingly performs physical operations. Though still a relatively new trend, these technologies are already demonstrating tangible benefits. According to industry reviews, AI implementation in construction contributes to reduced build times and material waste, improved project transparency, and more reliable adherence to deadlines. Most importantly, by integrating with BIM and other systems, AI helps establish a unified data environment in which all project information is leveraged for real-time decision-making. This represents a fundamentally new level of construction management that is gradually becoming the norm.

### **AI in the Operation Stage**

The operation phase of a building’s life cycle arguably offers the broadest opportunities for the application of artificial intelligence (AI). Once a facility is constructed and occupied, the focus shifts to efficient building management — from energy conservation to occupant comfort and timely equipment maintenance. Modern Building Management Systems (BMS) increasingly incorporate AI modules that analyze vast streams of sensor data and autonomously make decisions. As a result, the building can dynamically adjust its systems to real-time conditions, optimizing resource use without the need for human intervention.

One of the most prominent applications is in energy management — reducing a building’s energy consumption without compromising comfort. AI is already being used to address this challenge effectively. For instance, machine learning algorithms process data from thousands of sensors: temperature, lighting, occupancy, energy meters, weather forecasts, and even room booking schedules. Based on this information, AI systems control heating, ventilation, air conditioning (HVAC), and lighting in real time. They can also anticipate peak loads (e.g. using weather and usage forecasts) and proactively adjust equipment settings to flatten demand. Studies show that such intelligent systems can reduce energy consumption in commercial buildings by 20–30% compared to traditional controls. Furthermore, AI helps optimize energy distribution, making decisions on when to switch to backup generators or batteries, or when to charge storage systems based on electricity tariffs and solar generation forecasts. All of these adjustments are made automatically and continuously fine-tuned as new data becomes available.

Another key area is predictive maintenance of building systems. In traditional facility management, maintenance is often reactive — performed after a failure — or scheduled on a fixed timetable regardless of need. AI enables a shift toward anticipating equipment failures before they occur. Algorithms analyze sensor readings for vibration, temperature, pressure, equipment logs, and historical maintenance records. Based on this data, AI models detect early signs of deviation from normal operating parameters — indicators that a component may soon malfunction. For example, if the vibration pattern of a fan bearing exceeds statistical norms, the AI system can predict its failure within two weeks and alert the technical staff to schedule preventive replacement. This approach has proven effective: it reduces equipment downtime, extends service life, and lowers repair costs by 10–15% through the prevention of serious breakdowns. Reliability improves overall — for building owners and occupants, this translates to uninterrupted elevator service, heating, and power systems.

Large modern buildings are also starting to implement digital twins powered by AI. A digital twin is a virtual model of a building that remains synchronized in real time with the physical structure via

sensors and IoT devices. With AI, the digital twin not only reflects the current state but can simulate future operating scenarios [4]. For instance, if a ventilation fan fails, the digital twin can immediately show its impact on indoor temperatures and energy use, enabling fast response. Similarly, emergency scenarios can be simulated — such as evacuation during a fire — where AI calculates occupant flows and smoke extraction patterns, identifying critical choke points. This helps enhance safety during the operational phase. AI is also used in security and spatial management. Video surveillance systems with AI can detect suspicious activity or unauthorized access and instantly notify security personnel. Occupancy analytics, based on presence sensors and mobile data, allow for optimization of space use — such as identifying underused offices and enabling their repurposing.

In summary, during the operation phase, AI serves as the “brain” of a smart building. It continuously monitors all systems and their environment, learns from data, and strives to meet goals: occupant comfort, operational efficiency, safety, and sustainability. In practice, AI implementation at this stage offers the fastest economic returns, particularly through energy cost reductions. For example, in smart office environments, AI dynamically adjusts lighting and HVAC to match real-time occupancy, saving substantial electricity. In shopping centers, AI manages elevators and escalators, reducing operation during low-traffic hours. These often-invisible improvements collectively result in major gains in building efficiency. Finally, from a sustainability perspective, AI helps reduce the building’s environmental footprint — by optimizing water use, managing waste, and minimizing emissions through precise control of technical systems. Altogether, AI makes building operations significantly more rational and resource-efficient compared to traditional methods.

### **Benefits and Challenges of AI Implementation**

The results observed across various stages of the building life cycle demonstrate that the implementation of artificial intelligence (AI) in construction offers a wide array of benefits. Summarising the findings, the key advantages are as follows:

**Increased efficiency and cost reduction.** AI optimizes the use of resources — from construction materials to building energy — resulting in decreased operational and project costs. The automation of routine tasks enables more work to be completed in less time, accelerating both design and construction phases.

**Improved quality and accuracy.** AI algorithms reduce human error by automatically detecting issues during design (e.g. clash detection in BIM) [4] and construction (e.g. assembly errors, defects), thereby improving overall project quality. Predictive maintenance ensures high reliability of building systems throughout their service life.

**Enhanced safety.** Computer vision and data analytics systems offer improved enforcement of safety protocols on construction sites and enable real-time monitoring of building structures and engineering systems during operation. This contributes to reduced risk of accidents and improved protection of human health.

**Data-driven decision-making.** AI processes large volumes of data rapidly, providing project managers and building operators with actionable insights. As a result, planning, operational, and technical

decisions are made based on empirical evidence rather than intuition, enhancing their overall effectiveness.

Environmental sustainability. Intelligent algorithms help reduce the negative environmental impact of buildings by supporting energy efficiency, minimizing waste, and optimizing resource schedules. These improvements align with the goals of sustainable development.

However, alongside these advantages, there are several persistent challenges and barriers that hinder the widespread adoption of AI in the construction sector:

Shortage of qualified specialists. The industry lacks professionals with combined expertise in data science, machine learning, and construction. Surveys indicate that approximately 60% of large firms face difficulties hiring AI specialists. Upskilling engineers and attracting new talent is essential.

Data security and cyber risks. AI systems collect massive volumes of sensitive data about buildings and their occupants (from sensors, cameras, etc.). This raises concerns about the protection of personal information and the risk of cyberattacks. Clients and users must be confident that their data — including camera feeds and presence data — is securely handled and ethically managed.

Transparency and trust. Many AI algorithms operate as “black boxes,” with decisions that are difficult to interpret. This opacity creates mistrust among professionals — for instance, structural engineers may require clear justification for decisions made by AI. Ensuring model explainability and transparency is critical for broader acceptance.

High computational demands. Training and running complex AI models — especially those working with real-time data — require significant computing power. This contributes to growing data center energy consumption and associated costs. Some forecasts suggest that the rise of generative AI could double the energy use of global data centers by 2030. Striking a balance between AI benefits and its resource footprint is crucial.

High initial investment and implementation cost. While AI offers long-term cost savings, the entry threshold remains high. Investment in software, hardware, and staff training is required. For many organizations, especially small and medium-sized enterprises, this remains a barrier. Additionally, uncertainty around return-on-investment timelines often delays adoption decisions.

Lack of standards and regulatory frameworks. As previously noted, there is a global lack of unified standards for the use of AI and BIM in construction, particularly at the national level in many countries. This complicates the integration of diverse systems and the delineation of responsibilities. Standardized protocols, data requirements, and updated building codes are urgently needed. In the case of Uzbekistan, for example, there is a pressing need to officially adopt a comprehensive set of technical regulations for information modelling and life cycle management to create a regulatory foundation for AI deployment.

These barriers are gradually being addressed. Large firms are already investing in workforce digital training, cybersecurity frameworks for smart buildings are being developed, and research on explainable AI (XAI) is helping to make algorithms more interpretable. Governments in multiple

countries are beginning to draft guidelines and standards to support digital transformation in construction. Overcoming the outlined challenges is a key task for the coming years — and the extent to which they are resolved will determine how broadly and effectively AI will be adopted across the construction industry.

## Conclusion

The analysis has demonstrated that artificial intelligence (AI) holds immense potential to transform the entire building life cycle — from initial concept to long-term operation. In the design stage, AI empowers architects and engineers to make faster, more informed decisions by generating optimal solutions and predicting building performance. During construction, AI enhances project transparency and control, reduces the risk of delays and failures, and gradually automates labor-intensive tasks. In the operational phase, AI becomes the cornerstone of smart buildings — enabling adaptive systems that conserve resources, maintain comfort, and extend the service life of infrastructure.

The results achieved thus far are only the beginning. The benefits already realized by industry leaders are encouraging more companies to invest in AI. It is anticipated that over the next 5–10 years, AI adoption in construction will become widespread: generative design tools and digital twins will become part of the standard design toolkit; robots and AI-controlled drones will operate alongside human workers on construction sites; and every major building asset will be accompanied by its own intelligent digital replica. This will trigger a new leap in productivity and quality across architecture and construction — much like the transformation driven by CAD and BIM technologies in past decades.

To fully realize the potential of AI, coordinated efforts from all stakeholders are essential. Companies must invest in employee training and foster a data-centric culture. Technology providers should continue refining algorithms to make them more user-friendly and secure. Governments and industry bodies need to establish the regulatory frameworks and standards that enable digital transformation. In particular, Uzbekistan faces an urgent need to accelerate the adoption and implementation of technical standards for BIM and life cycle management, which will form the foundation for broad AI integration.

The use of AI across all stages of the building life cycle is no longer science fiction — it is an emerging reality. These technologies are poised to make buildings more economical, safer, and more environmentally sustainable, while enabling professionals to work more efficiently and creatively. By overcoming existing barriers, the construction sector in Uzbekistan — and worldwide — will be able to make a qualitative leap forward and build infrastructure equipped to meet the challenges of the 21st century.

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