

Innovations

Applications of Artificial Intelligence in Civil Engineering

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Abstract: *Artificial Intelligence (AI) is revolutionizing civil engineering by providing innovative solutions to complex problems, enhancing efficiency, and driving sustainability in infrastructure development. AI technologies, including machine learning, deep learning, computer vision, and neural networks, are increasingly applied across various civil engineering sectors, such as structural design, construction management, geotechnical engineering, transportation, and environmental engineering. By leveraging large datasets and advanced algorithms, AI can optimize structural designs, predict material performance, and improve project planning, leading to cost savings and reduced project timelines. AI-based systems also play a crucial role in structural health monitoring by analysing sensor data to detect early signs of damage or wear, allowing for predictive maintenance and extending the lifespan of infrastructure. In construction management, AI enhances resource allocation, risk management, and scheduling through data-driven decision-making, minimizing delays and cost overruns. In transportation, AI models contribute to traffic flow optimization, accident prediction, and efficient public transportation systems. Moreover, AI is instrumental in developing smart cities, optimizing energy use, and enhancing environmental monitoring and disaster management. The integration of AI in civil engineering enables the creation of safer, more resilient, and sustainable infrastructure. As AI continues to advance, its applications in civil engineering are expected to grow, addressing future challenges in urbanization, climate change, and resource management. This abstract highlights the transformative impact of AI on civil engineering, showcasing its potential to innovate and reshape the field, making it more adaptive and responsive to the evolving needs of society.*

Keywords: *Artificial intelligence, Machine learning, Structure health monitoring, Traffic signal, Smart cities, Civil engineering*

Introduction: The Integration of Artificial Intelligence in Civil Engineering

1. Overview of Artificial Intelligence and Its Evolution

Artificial Intelligence (AI) is a branch of computer science focused on creating systems capable of performing tasks that typically require human intelligence, such as learning, reasoning, problem-solving, and decision-making. Since its

inception in the 1950s, AI has evolved from simple rule-based systems to sophisticated machine learning models and neural networks that can analyse large volumes of data and identify complex patterns. The progression of AI technologies, including machine learning (ML), deep learning (DL), natural language processing (NLP), computer vision, and robotics, has opened new possibilities across various industries, including healthcare, finance, manufacturing, and notably, civil engineering.

Civil engineering, as a discipline, is concerned with the design, construction, and maintenance of infrastructure such as buildings, roads, bridges, dams, and airports. The field has always embraced technological advancements to improve efficiency, safety, and sustainability. As the demand for more innovative, cost-effective, and sustainable infrastructure continues to grow, the integration of AI offers unprecedented opportunities to revolutionize civil engineering practices. The application of AI in civil engineering is not just a trend but a transformative shift that enhances the capabilities of engineers to tackle complex problems and improve decision-making processes.

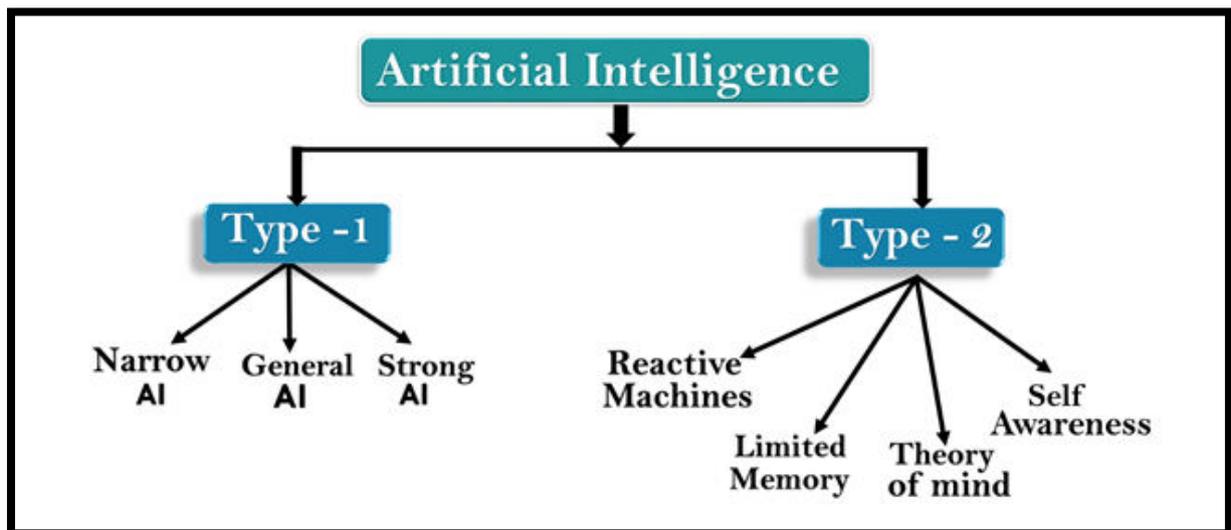


Fig. 10.1 Type of artificial intelligence

2. Relevance of AI in Civil Engineering

The relevance of AI in civil engineering stems from the need to address several challenges that the field faces today, including aging infrastructure, limited resources, labour shortages, and the pressing demand for sustainable development. Traditional methods of design, construction, and maintenance often rely on manual processes, empirical knowledge, and static models that may not be efficient or accurate enough for the modern demands of urbanization and climate change. AI, with its ability to process vast amounts of data, learn from

experience, and provide predictive insights, presents a solution to these challenges.

AI can analyse complex data sets generated from various sources, such as sensors, drones, satellite imagery, and Building Information Modelling (BIM) systems, to provide actionable insights. It enhances the accuracy of structural designs, optimizes resource allocation, improves safety protocols, and reduces operational costs. AI-driven models are also capable of predictive maintenance, identifying potential issues before they escalate into significant problems, thus extending the life of infrastructure and reducing the need for costly repairs.

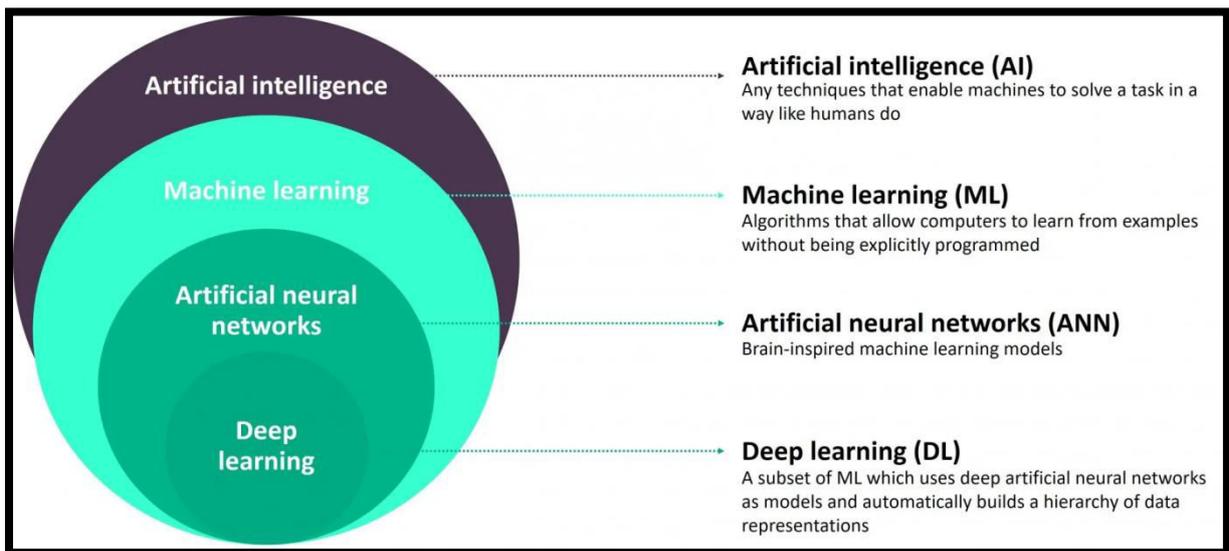


Fig. 10.3 Relationship between artificial intelligence, machine learning, and deep learning

3. Application of AI in Civil Engineering

3.1. Application of AI in Structural Analysis

Artificial Intelligence (AI) is increasingly being adopted in structural analysis within civil engineering to improve the design, assessment, and maintenance of structures. Traditional structural analysis methods rely on complex mathematical models and finite element analysis (FEA) to predict the behaviour of structures under various loads and conditions. However, these methods can be time-consuming and require significant computational resources, especially when dealing with large-scale or complex structures. AI, particularly through machine learning (ML), deep learning (DL), and neural networks, offers more efficient, data-driven approaches that enhance the accuracy, speed, and decision-making capabilities in structural engineering.

3.1.1. Structural Design Optimization:

AI has been instrumental in optimizing structural design, a process that involves selecting the best materials, dimensions, and configurations to achieve cost-effectiveness, safety, and sustainability. Machine learning algorithms can analyse historical data from numerous design projects, learn from past successes and failures, and suggest optimized design parameters. For example, AI can determine the optimal distribution of materials in a structure to reduce weight while maintaining strength, thus minimizing material costs and construction time.

3.1.2. Predictive Structural Health Monitoring:

Structural health monitoring (SHM) is crucial for ensuring the safety and longevity of infrastructure such as bridges, buildings, and dams. AI techniques, especially deep learning models like convolutional neural networks (CNNs) and recurrent neural networks (RNNs), are used to analyse data from sensors embedded in structures. These sensors collect data on parameters such as strain, vibration, temperature, and displacement. AI can process these large datasets to detect patterns indicative of structural damage or deterioration, such as cracks, corrosion, or excessive stress. By continuously monitoring and analysing the data in real-time, AI systems can provide early warnings about potential structural issues, allowing for proactive maintenance and avoiding catastrophic failures.

3.1.3. Automating Structural Damage Detection:

One of the significant applications of AI in structural analysis is automating damage detection and assessment. Traditional methods of structural inspection often involve manual, labour-intensive processes that are time-consuming and may not always be accurate. AI, particularly computer vision techniques combined with deep learning, can analyse images and videos from drones, cameras, or other remote sensing devices to automatically identify and classify types of damage, such as cracks, spalling, or deformation. This not only speeds up the inspection process but also enhances the accuracy of damage detection, ensuring that critical issues are addressed promptly.

3.1.4. Generative Design for Innovative Structures:

Generative design, an emerging AI-driven approach, allows for the creation of innovative structural forms that meet specific performance criteria. By defining constraints and objectives such as load capacity, material type, and safety factors, AI algorithms can generate numerous design alternatives and evaluate them against each criterion. This approach enables the discovery of novel structural solutions that may not be intuitive to human designers, leading to more efficient and aesthetically pleasing structures.

3.1.5. Enhancing Structural Simulation and Analysis:

AI is enhancing traditional simulation methods like finite element analysis (FEA) by reducing computational time and increasing accuracy. Machine learning models can learn from FEA simulations and predict structural responses under various loading conditions, effectively acting as surrogate models. This allows for faster analysis without compromising on precision, making it possible to evaluate a broader range of scenarios within shorter timeframes.

3.1.6. Adaptive Load Prediction and Risk Assessment:

AI systems are also used for adaptive load prediction and risk assessment. Machine learning models can predict future loads on structures, considering variables such as traffic patterns, weather conditions, and environmental factors. This helps engineers design structures that are more resilient to dynamic loading conditions and potential risks.

3.2. Application of AI in Concrete Technology

Artificial Intelligence (AI) is transforming concrete technology by optimizing material properties, improving mix designs, enhancing quality control, and advancing predictive maintenance practices. Concrete, as the most widely used construction material, is integral to civil engineering projects. However, its performance is influenced by numerous factors such as the mix proportions, environmental conditions, and curing processes. Traditional methods of optimizing concrete mix design and predicting performance often rely on empirical models and experience-based knowledge, which can be time-consuming and less precise. AI, particularly through machine learning (ML), deep learning (DL), and data-driven analytics, offers innovative approaches to address these challenges, resulting in more efficient, sustainable, and durable concrete structures.

3.2.1. Optimizing Concrete Mix Design:

AI plays a significant role in optimizing concrete mix design, which involves selecting the right proportions of cement, aggregates, water, and admixtures to achieve desired properties like strength, durability, and workability. Machine learning algorithms, such as artificial neural networks (ANNs) and support vector machines (SVMs), can analyse large datasets from previous mix designs and experimental results to predict the optimal mix proportions for specific performance criteria. This data-driven approach reduces the need for extensive trial-and-error methods, saving time and resources. AI models can also consider multiple constraints, such as cost, environmental impact, and material availability, to suggest the most cost-effective and sustainable concrete mix designs.

3.2.2. Enhancing Quality Control and Monitoring:

Quality control in concrete production is crucial for ensuring the durability and safety of structures. AI is being used to improve quality control processes by analysing data from sensors embedded in the concrete during mixing, transportation, and curing. Machine learning models can predict the final properties of concrete, such as compressive strength, based on real-time data from these sensors. For example, AI can monitor temperature, moisture content, and curing conditions to ensure optimal hydration and prevent defects like cracking or uneven strength distribution. By providing real-time feedback, AI enables better decision-making during construction and reduces the risk of defects that could compromise structural integrity.

3.2.3. Predictive Maintenance and Durability Assessment:

AI is increasingly used to predict the long-term performance and durability of concrete structures. Through deep learning models and data analytics, AI can analyse historical data on environmental exposure, load history, and material properties to predict potential deterioration, such as corrosion, cracking, or spalling. Predictive maintenance models use this data to recommend maintenance actions before significant damage occurs, extending the lifespan of concrete structures and reducing repair costs. This proactive approach to maintenance is particularly valuable in critical infrastructure, such as bridges, dams, and high-rise buildings, where failure can have catastrophic consequences.

3.2.4. Development of Sustainable Concrete:

AI contributes to the development of more sustainable concrete by optimizing the use of supplementary cementitious materials (SCMs) like fly ash, slag, and silica fume. These materials can replace a portion of cement in the mix, reducing carbon emissions and promoting the use of industrial by-products. AI models can determine the optimal proportions of SCMs to achieve the desired strength and durability while minimizing the environmental footprint of concrete production.

3.2.5. Smart Concrete with Self-Healing Properties:

AI is also being explored in the development of smart concrete with self-healing properties. By integrating AI algorithms with materials science, researchers can design concrete that can detect and heal cracks autonomously, using embedded microcapsules or bacteria that release healing agents when cracks occur. AI models help optimize the composition and activation mechanisms of these smart materials, enhancing their effectiveness and applicability in real-world scenarios.

3.3. Application of AI in Construction Management

Artificial Intelligence (AI) is reshaping construction management by enhancing efficiency, reducing costs, improving safety, and optimizing resource allocation.

The construction industry has traditionally been slow to adopt new technologies due to its complex, dynamic, and fragmented nature. However, with the growing challenges of labour shortages, cost overruns, project delays, and the increasing demand for sustainable and smart buildings, AI is emerging as a game-changer. By leveraging AI techniques such as machine learning (ML), computer vision, natural language processing (NLP), and robotics, construction management can achieve significant advancements in project planning, risk management, quality control, and safety.

3.3.1. Project Planning and Scheduling:

AI is transforming project planning and scheduling by analysing historical data and identifying patterns that help predict potential delays, resource shortages, and budget overruns. Machine learning algorithms can process vast amounts of data from past projects, such as timelines, costs, and resource utilization, to generate optimized schedules and allocate resources more efficiently. These AI models can consider multiple constraints—such as weather conditions, labour availability, and supply chain disruptions—to provide more accurate and dynamic project timelines. This predictive capability enables construction managers to anticipate and mitigate risks, ultimately leading to more efficient project delivery.

3.3.2. Risk Management and Mitigation:

Risk management is a critical aspect of construction management, given the industry's inherent uncertainties and complexities. AI-powered tools can help identify potential risks early in the project lifecycle by analysing data from various sources, including contract documents, safety records, and project plans. Natural language processing (NLP) algorithms can scan and interpret large volumes of unstructured data to highlight areas of concern, such as ambiguous contract clauses or historical safety violations. Machine learning models can then assess the likelihood of risks, such as cost overruns or safety incidents, and suggest mitigation strategies. This proactive approach to risk management improves decision-making and helps in maintaining project timelines and budgets.

3.3.3. Quality Control and Assurance:

AI technologies, particularly computer vision, are revolutionizing quality control processes on construction sites. Drones and cameras equipped with AI algorithms can monitor construction activities in real-time, capturing high-resolution images and videos. Computer vision models can analyse this data to detect deviations from design specifications, identify construction defects, and ensure compliance with safety and quality standards. For example, AI can automatically identify issues like misaligned beams, incorrect installations, or cracks in concrete, allowing for immediate corrective actions. This reduces the

reliance on manual inspections, which are time-consuming and prone to human error, thereby enhancing overall construction quality.

3.3.4. Safety Management:

Safety is a major concern in construction management due to the high-risk environment of construction sites. AI is playing a vital role in enhancing safety management by using computer vision and real-time data analysis. AI algorithms can analyse live feeds from cameras to detect safety hazards, such as workers not wearing protective gear, unsafe scaffolding, or proximity to heavy machinery. Alerts can be generated immediately to prevent accidents. Furthermore, AI models can analyse historical safety data to predict potential accidents and implement preventive measures, significantly reducing the rate of workplace injuries.

3.3.5. Resource Optimization and Cost Control:

AI helps optimize resource allocation by analysing project requirements and predicting the most efficient use of labour, materials, and equipment. Machine learning models can forecast material needs based on project progress, minimizing waste and reducing costs associated with over-ordering or delays due to shortages. AI tools also assist in managing equipment by predicting maintenance needs, preventing breakdowns, and extending the lifespan of machinery.

3.3.6. Enhancing Communication and Collaboration:

AI-driven platforms are improving communication and collaboration among stakeholders in construction projects. AI can automate document management, provide real-time updates, and streamline communication channels between architects, engineers, contractors, and clients. This reduces misunderstandings, accelerates decision-making, and ensures that all parties are aligned with project goals.

3.4. Application of AI in Transportation Engineering

Artificial Intelligence (AI) is transforming transportation engineering by optimizing traffic management, enhancing road safety, improving public transportation systems, and enabling the development of autonomous vehicles. Transportation engineering, which deals with the planning, design, operation, and maintenance of transportation systems, faces numerous challenges such as traffic congestion, accident prevention, and the need for sustainable mobility solutions. AI, through machine learning (ML), deep learning (DL), computer vision, and data analytics, offers innovative solutions that significantly enhance the efficiency, safety, and sustainability of transportation networks.

3.4.1. Traffic Management and Congestion Control:

AI is revolutionizing traffic management by providing intelligent solutions for real-time traffic monitoring and control. Machine learning algorithms analyse data from various sources such as traffic cameras, GPS, sensors, and social media to predict traffic patterns, identify congestion hotspots, and suggest optimal traffic signal timings. AI-powered traffic management systems use this data to dynamically adjust traffic signals and reroute vehicles to less congested routes, reducing delays and fuel consumption. For instance, AI algorithms can analyse the flow of vehicles at intersections and make real-time adjustments to traffic lights to optimize traffic flow, thereby minimizing congestion and improving the overall efficiency of urban road networks.

3.4.2. Predictive Maintenance and Infrastructure Management:

AI is employed in predictive maintenance of transportation infrastructure, such as roads, bridges, and railways, to ensure their safety and longevity. By analysing data from sensors embedded in the infrastructure, AI models can predict potential failures or deterioration due to wear and tear, extreme weather conditions, or increased traffic loads. Predictive maintenance models use machine learning to analyse patterns of deterioration and suggest timely interventions, preventing costly repairs and enhancing safety. This proactive approach helps transportation authority's prioritize maintenance activities and allocate resources more efficiently.

3.4.3. Enhancing Road Safety and Accident Prevention:

AI plays a crucial role in enhancing road safety by analysing large datasets related to traffic accidents, driver behaviour, and road conditions. AI-powered systems can predict high-risk scenarios and provide early warnings to drivers or traffic control centres. For example, computer vision algorithms can analyse live video feeds from road cameras to detect potential hazards, such as pedestrians crossing unexpectedly, vehicles swerving, or objects on the roadway. AI can also be integrated with connected vehicle technology, allowing vehicles to communicate with each other and with infrastructure to avoid collisions and improve overall road safety.

3.4.4. Autonomous and Connected Vehicles:

The development of autonomous vehicles (AVs) is one of the most significant advancements driven by AI in transportation engineering. Autonomous vehicles rely heavily on AI algorithms for perception, decision-making, and navigation. Machine learning and deep learning models enable AVs to recognize objects, detect lanes, interpret traffic signals, and make real-time decisions based on the driving environment. AI also plays a critical role in vehicle-to-everything (V2X) communication, which allows AVs to interact with each other and with traffic infrastructure, optimizing traffic flow and enhancing safety. The widespread

adoption of AVs is expected to reduce traffic accidents, improve fuel efficiency, and transform urban mobility.

3.4.5. Public Transportation Optimization:

AI is being used to optimize public transportation systems, including buses, trains, and metro networks, by analysing passenger demand, travel patterns, and real-time traffic data. Machine learning algorithms can forecast peak travel times, optimize routes, and improve schedule adherence. AI-driven predictive analytics helps public transit agencies allocate resources more effectively, reducing wait times and improving service reliability. Additionally, AI can enhance the passenger experience by providing personalized travel recommendations, real-time updates, and dynamic pricing models.

3.4.6. Smart City Integration and Sustainable Mobility:

AI is integral to the development of smart cities by integrating transportation systems with other urban services. AI-driven models analyse data from various urban sensors to optimize energy use, reduce emissions, and promote sustainable mobility solutions like electric vehicles and shared mobility services. AI enables more efficient urban planning by analysing transportation data to design better road networks, bike lanes, and pedestrian zones, contributing to greener and more liveable cities.

3.5. Application of AI in Green Building

Artificial Intelligence (AI) is playing a transformative role in green building, which aims to enhance sustainability, energy efficiency, and environmental performance in construction and operation. Green buildings are designed to minimize their ecological footprint by optimizing resource use, reducing waste, and improving indoor environmental quality. AI, through machine learning (ML), data analytics, and intelligent systems, provides innovative solutions to achieve these goals, making buildings smarter, more efficient, and environmentally friendly.

3.5.1. Energy Management and Optimization:

AI significantly enhances energy management in green buildings by optimizing heating, ventilation, and air conditioning (HVAC) systems, lighting, and energy consumption. Machine learning algorithms analyse data from various sources, including sensors, weather forecasts, and occupancy patterns, to predict and adjust energy usage in real-time. For example, AI systems can learn from historical data to identify patterns in energy consumption and recommend adjustments to HVAC settings or lighting schedules to reduce energy waste. AI-powered smart grids and energy management systems can also integrate renewable energy sources, such as solar or wind, to optimize energy distribution and storage, further enhancing the building's sustainability.

3.5.2. Predictive Maintenance and Building Performance:

AI is used for predictive maintenance by analysing data from building systems and equipment to predict potential failures or inefficiencies. Machine learning models can process sensor data to detect anomalies and predict when maintenance is required, reducing downtime and extending the lifespan of equipment. This proactive approach ensures that building systems operate at peak performance, minimizes disruptions, and reduces the need for emergency repairs, contributing to overall sustainability.

3.5.3. Smart Building Design and Simulation:

AI contributes to the design and simulation of green buildings by optimizing architectural and engineering elements for energy efficiency and environmental performance. Generative design algorithms use AI to explore a wide range of design options based on parameters such as energy performance, material use, and spatial requirements. This approach allows architects and engineers to identify the most sustainable design solutions that meet performance criteria while minimizing environmental impact. AI-driven simulation tools also help in assessing the impact of various design choices on energy consumption, indoor air quality, and overall building performance.

3.5.4. Indoor Environmental Quality (IEQ) Optimization:

AI improves indoor environmental quality (IEQ) by analysing data from sensors that monitor air quality, temperature, humidity, and lighting conditions. Machine learning algorithms can identify patterns and correlations between different environmental factors and occupant comfort, adjusting building systems to maintain optimal conditions. For example, AI systems can automatically adjust ventilation rates to ensure adequate fresh air supply and control lighting to enhance occupant well-being and productivity. By improving IEQ, AI contributes to healthier and more comfortable indoor environments.

3.5.5. Resource Efficiency and Waste Reduction:

AI helps in optimizing resource use and reducing waste during construction and operation. Machine learning models can analyse data on material usage, construction processes, and waste generation to identify opportunities for resource efficiency. AI-driven tools can recommend sustainable materials, optimize material quantities, and minimize construction waste. Additionally, AI can monitor water usage and suggest conservation measures, further supporting the building's sustainability goals.

3.5.6. Occupancy and Behaviour Analysis:

AI enhances the understanding of occupant behaviour and its impact on building performance. By analysing data from occupancy sensors, smart meters, and user interactions, AI systems can identify patterns in how spaces are used and adjust

building systems accordingly. This analysis helps in optimizing space utilization, reducing energy consumption, and improving overall building efficiency. AI can also provide personalized recommendations to occupants for energy-saving behaviours and enhance user engagement in sustainability initiatives.

4. Future Perspectives of AI in Civil Engineering

The future of AI in civil engineering is promising, with advancements in technology expected to further revolutionize the field. Emerging AI technologies, such as reinforcement learning, generative design, and advanced robotics, are anticipated to enhance the capabilities of civil engineers even further. The integration of AI with other cutting-edge technologies, such as IoT, blockchain, and digital twins, will create more intelligent, autonomous, and resilient infrastructure systems.

In addition, AI-driven smart cities, automated construction sites, and sustainable urban planning models are likely to become the norm. Collaborative AI systems, where humans and machines work together to solve complex engineering problems, will lead to more innovative and adaptive solutions. As AI continues to evolve, it will play a pivotal role in addressing global challenges such as urbanization, climate change, and resource scarcity, making civil engineering more efficient, sustainable, and responsive to the needs of society.

References

- [1] J. Zhu, T. Lan, and W. Wang, "An AI-driven design exploration framework for optimization of pedestrian bridge," *Journal of Computing in Civil Engineering*, vol. 31, 2017.
- [2] X. Zhao, W. Ren, and Y. Li, "Fuzzy logic based computational intelligence for structural analysis," *Structure and Infrastructure Engineering*, vol. 13, no. 2, pp. 227–239, 2017.
- [3] Y. Zhang, C. Huang, J. Zhang, Y. Chen, and Z. Wu, "Predicting the flexural behaviour of FRP-reinforced concrete beams using artificial neural networks," *Advances in Civil Engineering*, vol. 20, 2020.
- [4] L. Zhang, S. Li, Y. Gong, and Y. M. Xie, "Shape optimization of truss structures using generative adversarial network," *Computer-Aided Design*, vol. 125, no. 2, 2020.
- [5] J. Zhang, R. X. Gao, and R. Yan, "An intelligent modal parameter identification method for structural health monitoring," *Structural Health Monitoring*, vol. 14, no. 6, pp. 618–633, 2015.
- [6] C. Zhang, M. Wu, K. Zhou, B. Li, and G. Yan, "Improved structure design optimization via neural network-based surrogate modelling and parallel

- MOEA/D," *Automation in Construction*, vol. 114, 2020.
- [7] A. Zahedi, A. Nafisi, and A. Afshar, "Fuzzy analytic hierarchy process for material selection in bridge construction," *Journal of Performance of Constructed Facilities*, vol. 34, no. 2, 2020.
- [8] K. Yin, W. Huang, and X. Xu, "Landslide susceptibility analysis using deep neural networks: A case study in Chongqing," *China. Engineering Geology*, vol. 276, no. 2, 2020.
- [9] Z. Wu, H. Qian, and L. Li, "Multi-objective optimization for steel truss design using a modified genetic algorithm," *Advances in Structural Engineering*, vol. 19, no. 6, pp. 1023–1034, 2016.
- [10] S. Wu, Z. Yi, Z. Li, and Y. Wang, "Application of machine learning approaches to material selection in concrete pavement design," *Journal of Computing in Civil Engineering*, 2017.
- [11] C. Wu, S. Yang, H. Xiong, and S. Ye, "Artificial intelligence in civil engineering: Recent advances and future trends," *Frontiers of Engineering Management*, vol. 7, no. 3, pp. 332–342, 2019.
- [12] A. Wibowo, S. Roshani, P. A. Fosu, and A. Gospodini, "Review of artificial intelligence in buildings: Opportunities, challenges, and methodologies," *Building and Environment*, vol. 182, 2020.
- [13] D. Wang and L. Liu, "Construction project scheduling optimization using particle swarm optimization integrated with cloud computing and machine learning," *Automation in Construction*, vol. 110, no. 2, 2020.
- [14] M. R. Tabeshpour, M. Sheikhzadeh, A. R. Rahai, and M. R. Banan, "Steel truss optimization using deep neural network and genetic algorithm," *Journal of Computing in Civil Engineering*, vol. 35, 2021.
- [15] I. Sutskever, O. Vinyals, and Q. V. Le, "Sequence to sequence learning with Neural Networks," *arXiv [cs.CL]*, 2014.
- [16] Z. Sun, W. Huang, Z. Zhou, and J. Wang, "Prediction model for cracking performance of asphalt pavements using machine learning methods," *Journal of Transportation Engineering*, vol. 146, 2020.
- [17] W. Sun, Q. Chen, S. Li, and R. Yu, "Machine learning-based prediction of mechanical properties of cement-based materials using X-ray micro-computed tomography images," *Automation in Construction*, vol. 99, pp. 34–45, 2019.
- [18] I. F. Smith, M. Z. Elshafie, and A. F. Sadullah, "Machine learning applications in civil engineering," *Civil Engineering Journal*, vol. 4, no. 5, pp. 1130–1142, 2018.
- [19] Y. Shan, Q. Guo, D. Li, and C. Zhang, "Optimization model for bike-sharing station configuration based on evolutionary algorithm," *Journal of Advanced Transportation*, vol. 20, 2018.
- [20] M. P. Saka and N. Kumbasar, "Structural design optimization of steel trusses using genetic algorithms," *Advances in Engineering Software*, vol. 102, pp. 12–

21, 2016.

- [21] S. Russell and P. Norvig, *Artificial Intelligence: A Modern Approach*. Pearson, 2016.
- [22] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, "Learning Representations by Backpropagating Errors," *Nature*, vol. 323, no. 6088, pp. 533–536, 1986.
- [23] F. R. Rofooei, A. Kaveh, and F. F. Masteri, "Estimating the vulnerability of concrete moment resisting frame structures using artificial neural networks," *International Journal of Operational Research*, vol. 1, no. 3, pp. 433–448, 2011.
- [24] T. H. Nguyen, V. T. Nguyen, and H. T. Nguyen, "An AI-driven decision support system for structural health monitoring of bridges," *Engineering Structures*, vol. 204, no. 2, 2020.
- [25] Y. Li, Q. Liu, J. Zhou, and X. Zhou, "Artificial intelligence in construction safety management: State-of-the-art and future trends," *Journal of Construction Engineering and Management*, vol. 147, 2021.
- [26] H. Li, Y. Ma, and C. M. Wang, "Automated detection of crack patterns in concrete structures using convolutional neural networks," *Journal of Computing in Civil Engineering*, vol. 35, no. 2, 2021.
- [27] A. Kaveh, "A metaheuristic-based artificial neural network for plastic limit analysis of frames," in *Applications of Artificial Neural Networks and Machine Learning in Civil Engineering*, Cham: Springer Nature Switzerland, 2024, pp. 257–268.
- [28] A. Kaveh, "Efficient training of two ANNs using four meta-heuristic algorithms for predicting the FRP strength," in *Applications of Artificial Neural Networks and Machine Learning in Civil Engineering*, Cham: Springer Nature Switzerland, 2024, pp. 359–388.
- [29] A. Bhoopalam, D. Patel, and A. Bhaskar, "Generative design approach for low-cost pedestrian bridge: An artificial intelligence-based structural optimization," *Structures*, vol. 33, pp. 1900–1913, 2021.
- [30] V. Aravantinos, E. N. Chatzi, C. Papadimitriou, and E. Ntotsios, "A novel AI-based methodology for vibration-based structural health monitoring," *Mechanical Systems and Signal Processing*, vol. 135, 2020.

