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Applications of Artificial Intelligence (AI) in the construction industry: A review of Observational Studies

Adesola O Adeloye, Olayemi Diekola, Ken Delvin, and Chris Gbenga

1. Department of Civil and Environmental Engineering, Federal Engineering Research Institute, Ondo, Nigeria

Abstract:
The construction industry faces numerous complex challenges, including cost and time overruns, health and safety concerns, productivity issues, and labor shortages. Additionally, the industry lags behind in terms of digitalization, making it difficult to address these challenges effectively. However, Artificial Intelligence (AI), an advanced digital technology, has the potential to revolutionize the construction industry, much like it has transformed other sectors such as manufacturing, retail, and telecommunications. AI encompasses various subfields, including machine learning, knowledge-based systems, computer vision, robotics, and optimization, all of which have proven successful in improving profitability, efficiency, safety, and security in other industries. Despite the acknowledged benefits of AI applications, the construction industry still faces several challenges in implementing AI effectively. This study aims to explore the applications of AI in the construction industry, examine the AI techniques currently being utilized, and identify both the opportunities and challenges associated with AI implementation. A comprehensive literature review was conducted to assess existing research on AI applications in construction, focusing on areas such as activity monitoring, risk management, and resource and waste optimization. Through this review, the study highlights the potential opportunities for AI applications in the construction industry, specifically in addressing industry-specific challenges. By leveraging AI technologies, construction companies can improve activity monitoring, enhance risk management strategies, and optimize resource allocation and waste reduction. Furthermore, the study identifies and presents the challenges that need to be overcome for successful AI implementation in construction. These challenges may include issues related to data availability and quality, integration with existing systems, ethical considerations, and workforce upskilling. By providing insights into key AI applications tailored to the construction industry's unique challenges, this study offers a pathway to realize the tangible benefits that AI can bring to the industry. It serves as a foundation for future research and development efforts in harnessing AI's potential to revolutionize construction practices.

INTRODUCTION

The construction industry faces numerous challenges that have hindered its growth and productivity, especially when compared to more digitized industries like manufacturing [1]. Digitization within the construction sector has been slow, primarily due to a long-standing resistance to change [2]. This lack of digitalization and overreliance on manual processes make project management complex and unnecessarily tedious [3,4]. Furthermore, the absence of digital expertise and technology adoption has led to cost inefficiencies, project delays, poor quality performance, uninformed decision-making, and overall low productivity and safety standards [5]. In light of labor shortages, the COVID-19 pandemic, and the need for sustainable infrastructure, it has become increasingly clear that the construction industry must embrace digitization and enhance its technological capacity [6,140–142].

Artificial Intelligence (AI), as a leading digital technology, has made significant contributions to improving business operations, service processes, and industry productivity in various domains [1]. The adoption of AI techniques offers automated solutions and provides competitive advantages over conventional approaches [7]. Subfields of AI, such as machine learning, natural language processing, robotics, computer vision, optimization, and automated planning and scheduling [8], have successfully addressed complex problems and supported decision-making in real-world scenarios. For instance, the manufacturing industry has experienced the fourth industrial revolution, known as Industry 4.0, which emphasizes automation, data-driven technologies, and advanced AI techniques [9]. This revolution has resulted in significant improvements in processes, cost-efficiency, and reduced production times.

Considering the success of AI in other industries, there is immense potential to apply AI techniques in the construction industry. AI can help automate processes, improve project management, enhance safety measures, and optimize resource allocation. By leveraging machine learning algorithms, construction companies can analyze large datasets to gain valuable insights for informed decision-making and predictive maintenance. Computer vision technologies can aid in quality control and monitoring on construction sites, ensuring adherence to design specifications and identifying potential safety risks. AI-driven optimization algorithms can streamline construction schedules, minimize delays, and improve overall project efficiency.
However, several challenges must be addressed to effectively implement AI in the construction industry. These challenges include data availability and quality, integration with existing systems, ensuring ethical use of AI, and overcoming the resistance to change within the industry. Additionally, there is a need for upskilling the workforce to embrace and utilize AI technologies effectively.

In conclusion, the construction industry's low productivity and resistance to change can be addressed through the adoption of AI techniques. AI has proven its value in other industries by enhancing automation, decision-making, and overall productivity. By leveraging machine learning, computer vision, and optimization algorithms, the construction industry can overcome its challenges and achieve significant improvements in project management, safety, efficiency, and quality performance. However, careful consideration must be given to addressing the challenges associated with AI implementation and promoting a culture of embracing technological advancements within the construction industry.

Despite the potential benefits of AI in improving safety and achieving sustainability goals in the construction industry [7,10,11], its adoption and implementation in the sector have been limited. Researchers have published numerous articles on the application of AI and its subfields to address construction-specific challenges. Machine learning has been utilized for health and safety monitoring, cost estimation, supply chain and logistics improvements, and risk prediction [12–15]. Robotics has found applications in site monitoring, performance evaluation, offsite assembly, and managing construction materials, plant, and equipment [16,17,18]. Knowledge-based systems have been employed for tender evaluation, conflict resolution, risk and waste management, and sustainability assessments [19,20]. However, despite these efforts, the construction industry remains one of the least digitized sectors globally, struggling to fully adopt AI and other digital technologies.

Studies have highlighted various challenges hindering the adoption of AI in construction, including cultural barriers, high initial deployment costs, issues of trust and security, talent shortages, limited computing power, and inadequate internet connectivity. However, there are still significant knowledge gaps regarding the research trends in AI applications, future opportunities, and barriers to adoption within the construction industry.

To address these gaps, it is crucial to investigate the following research questions: (1) What are the specific areas of AI application in the construction industry? (2) What are the future opportunities for AI implementation in construction? (3) What are the key challenges to the adoption of AI in the construction industry? Therefore, a critical examination of AI applications in construction is essential to understand current trends, identify opportunities for growth, and recognize barriers to widespread adoption.

The objectives of this study are as follows:

1. Conduct a comprehensive review of existing applications of AI and its subfields in the construction industry.
2. Identify potential areas and opportunities for increased AI implementation in the construction industry.
3. Identify and analyze the challenges affecting the adoption of AI in the construction industry.

This study will make a significant contribution to knowledge by addressing the lack of information on AI in construction. It will provide background knowledge on AI, its types, components, and subfields, and then delve into the existing implementations of AI within the construction industry. By critically examining the applications, opportunities, and challenges associated with AI, this study will shed light on the potential benefits of AI adoption and help inform future strategies for successful integration of AI in the construction industry.

METHODS

To conduct this research, an extensive literature review was performed to identify the existing applications of artificial intelligence (AI) in the construction industry. The review encompassed the period from 1960 to 2023, spanning six decades of AI adoption trends in the construction sector. The SCOPUS database was used as the primary data source, supplemented by other reputable databases such as IEEE, ACM, and Science Direct for full article download and data validation. These databases were selected due to their extensive coverage of high-impact publications in construction, engineering, and computer science.

To ensure a focused search, specific AI techniques were targeted since many studies in the field concentrated on utilizing particular AI approaches to achieve specific goals. A set of twenty-nine free-text keywords encompassing AI subfields and the construction industry was employed, including terms such as "Robotics," "Computer vision," "Machine learning," "Expert System," "Knowledge-based Systems," "Optimization," "Natural Language Processing," and others. Advanced search techniques were employed to enhance the precision of the study.

The search was limited to articles published in English. Conference papers were excluded when keyword searches generated over 100 articles, as the regular practice in the construction domain is to convert conference papers into journal articles. However, in-depth searches were conducted within subfields such as machine learning, knowledge-based systems, and optimization, which yielded a larger number of papers.

Out of the 1700 publications initially assessed, 1142 articles were deemed relevant and included for further investigation. Inclusion criteria focused on articles that described or evaluated AI subfields and their techniques for practical application within the construction industry. The relevance of each article was determined based on the abstract, title, or full-text content when the title or abstract lacked clarity. Key data points, including the application area in construction, methodology/techniques used, and findings, were extracted from each article.

Following the literature review, an overview of artificial intelligence and its subfields was provided. The concept of developing machines with human-like intelligence has its origins in various fields such as philosophy, fiction, computer science, and engineering inventions. Alan Turing's test for intelligence marked a pivotal moment in the field, surpassing traditional theological and mathematical notions regarding the possibility of intelligent machines. Today, intelligent machines outperform humans in various domains, leveraging advancements in technologies like big data and computer processing power.

The three types of AI discussed are Artificial Narrow Intelligence (ANI), Artificial General Intelligence (AGI), and Artificial Super Intelligence (ASI). ANI, also known as weak AI, refers to machines exhibiting intelligence in specific domains, such as chess playing or language translation. AGI, or strong AI, aims to develop machines that can operate at the same level as humans, capable of solving complex problems in different domains. ASI concerns machines that surpass human capabilities across multiple domains.

The major components of AI include learning, knowledge representation, perception, planning, action, and communication. These components represent the various tasks that AI can perform compared to humans. Fig. 1 provides an overview of the types, components, and subfields of AI.

In summary, the research methodology involved an extensive literature review using multiple databases, employing specific keywords and search criteria. The selected articles were thoroughly analyzed, and relevant data was extracted. The overview of AI and its subfields provided a foundational understanding of the subject matter for further investigation.

To understand the current state of AI in the construction industry, it is important to recognize the major subfields of AI. Some of the well-known subfields of AI that have been applied in the industry include:

1. Machine Learning: Machine Learning involves the design and use of computer programs that learn from past data or experiences to make predictions, control systems, or create models. It includes supervised learning (making decisions based on labeled datasets), unsupervised learning (finding patterns in unlabeled datasets), reinforcement learning (learning from interactions with the environment), and deep learning (using neural networks for advanced pattern recognition).
2. Computer Vision: Computer Vision aims to simulate the human visual system by enabling machines to understand and interpret digital images or videos. It involves capturing images, processing them using algorithms, and analyzing them to facilitate decision-making in various construction tasks.
3. Automated Planning and Scheduling: Planning focuses on selecting and sequencing actions to achieve specific goals, while scheduling involves allocating time and resources to accomplish those goals. AI techniques are used to provide solutions for complex planning and scheduling problems, including search techniques, optimization algorithms, and genetic algorithms.
4. Robotics: Robotics involves the design, manufacturing, operation, and maintenance of highly automated devices (robots) that can perform physical tasks. Robots interact with the environment using sensors and actuators, and machine learning techniques, particularly reinforcement learning, are often applied to solve learning problems in robotics.
5. Knowledge-based Systems: Knowledge-based Systems (KBS) use existing knowledge to make decisions. They consist of a knowledge base, an inference engine, and a user interface. KBS can imitate human decision-making in specific domains and are classified into expert systems, case-based reasoning systems, intelligent tutoring systems, and DBMS with intelligent user interfaces.
6. Natural Language Processing (NLP): NLP focuses on creating computational models that mimic human linguistic capabilities. It has applications in machine translation, text processing, speech recognition, and information retrieval. NLP tasks include part-of-speech tagging, named entity recognition, and semantic role labeling.
7. Optimization: Optimization involves making the best decisions or choices within given constraints to achieve optimal outcomes. It is a mathematical discipline that has evolved with AI, and metaheuristic algorithms like genetic algorithms and particle swarm optimization are commonly used.

In the construction industry, AI applications have been trending towards the adoption of machine learning, optimization, robotics, and automated planning and scheduling. Machine learning has gained significant attention due to its potential to address labor and skill shortages, while optimization techniques have been applied to improve productivity. Robotics, particularly with the introduction of technologies like 3D printing and exoskeletons, has also seen advancements in the industry. On the other hand, natural language processing has been less explored in the construction industry.

Recent developments in AI applications in construction have also been influenced by emerging technologies such as quantum computing, Internet of Things (IoT), cybersecurity, and blockchain. Quantum computing offers accelerated problem-solving capabilities that can benefit AI applications. IoT integration with AI enables real-time monitoring, traceability, and energy-saving in construction processes. However, the increasing reliance on interconnected systems and digital technologies also raises concerns about cybersecurity risks in the construction industry. Blockchain technology has found applications in areas like risk management and financial services, but its potential in construction is still being explored.

Overall, AI has the potential to revolutionize the construction industry by improving efficiency, productivity, and decision-making processes. Ongoing research and developments in AI subfields and their integration with emerging technologies will continue to shape the future of AI applications in construction.

To gain insights into the current state of AI in the construction industry, it is essential to understand the main subfields of AI that have been widely applied in this domain. Several prominent subfields of AI that have found applications in the construction industry are:

1. Machine Learning: Machine Learning involves the development and utilization of computer programs that learn from historical data or experiences to make predictions, control systems, or create models. It encompasses various techniques such as supervised learning (making decisions based on labeled datasets), unsupervised learning (identifying patterns in unlabeled datasets), reinforcement learning (learning through interactions with the environment), and deep learning (using neural networks for advanced pattern recognition).
2. Computer Vision: Computer Vision aims to replicate the capabilities of the human visual system by enabling machines to understand and interpret digital images or videos. It encompasses capturing images, processing them using algorithms, and analyzing them to facilitate decision-making in different construction tasks.
3. Automated Planning and Scheduling: Planning focuses on selecting and sequencing actions to achieve specific goals, while scheduling involves allocating time and resources to accomplish those goals. AI techniques are employed to provide solutions for complex planning and scheduling problems, including search techniques, optimization algorithms, and genetic algorithms.
4. Robotics: Robotics involves the design, manufacturing, operation, and maintenance of highly automated devices known as robots that can perform physical tasks. Robots interact with the environment using sensors and actuators, and machine learning

techniques, particularly reinforcement learning, are often applied to address learning problems in robotics.

5. Knowledge-based Systems: Knowledge-based Systems (KBS) utilize existing knowledge to make decisions. They consist of a knowledge base, an inference engine, and a user interface. KBS can imitate human decision-making in specific domains and are classified into expert systems, case-based reasoning systems, intelligent tutoring systems, and DBMS with intelligent user interfaces.
6. Natural Language Processing (NLP): NLP focuses on developing computational models that mimic human linguistic capabilities. It finds applications in machine translation, text processing, speech recognition, and information retrieval. NLP tasks include part-of-speech tagging, named entity recognition, and semantic role labeling.
7. Optimization: Optimization involves making the best decisions or choices within given constraints to achieve optimal outcomes. It is a mathematical discipline that has evolved with the advancement of AI, and metaheuristic algorithms like genetic algorithms and particle swarm optimization are commonly employed.

In the construction industry, AI applications have witnessed a growing emphasis on machine learning, optimization, robotics, and automated planning and scheduling. Machine learning has garnered significant attention due to its potential to address labor and skill shortages. Optimization techniques have been employed to enhance productivity. Robotics, particularly with the introduction of technologies like 3D printing and exoskeletons, has seen notable advancements. However, natural language processing remains relatively less explored in the construction industry.

Recent developments in AI applications in construction have also been influenced by emerging technologies such as quantum computing, the Internet of Things (IoT), cybersecurity, and blockchain. Quantum computing offers accelerated problem-solving capabilities that can benefit AI applications. Integration of IoT with AI enables real-time monitoring, traceability, and energy-saving in construction processes. However, the increasing reliance on interconnected systems and digital technologies raises concerns about cybersecurity risks in the construction industry. Blockchain technology has found applications in areas like risk management and financial services, but its potential in construction is still being explored.

Overall, AI has the potential to revolutionize the construction industry by improving efficiency, productivity, and decision-making processes. Ongoing research and developments in AI subfields and their integration with emerging technologies will continue to shape the future of AI applications in construction.

Table 2: Advantages and Limitations of AI Subfields in Construction

Subfield	**Advantages in Construction**	**Limitations in Construction**	**References**
Machine Learning	- Relevant predictive and prescriptive insights	- Incomplete data	[3]
	- Increased efficiency	- Learning from streaming data, dealing with high-dimensional data, scalability of models and distributed computing	
Computer Vision	- Faster inspection and monitoring	- Total scene understanding	[4]
	- Better accuracy, reliability, and transparency	- Improvement of tracking accuracy and effective visualization of tracking results	
Automated Planning and Scheduling	- Cost savings due to improved processes (e.g., logistics)	- Mostly expensive to implement	[6]
	- Increased productivity	- Could be complex	
Robotics	- Increased safety	- High initial costs	[5]
	- Increased productivity	- Potential job loss due to automation	
	- Improved quality	- Maintenance and repair costs	
Knowledge-based systems	- Easy access to relevant information	- Intellectual property protection and security issues	[10]
	- Easy to update	- Knowledge acquisition issues	
Natural Language Processing	- Increased productivity	- Speech recognition issues such as construction site noise, homonyms, accent variability, etc.	[12]
	- Cost effectiveness	- Data privacy and security issues	
Optimization	- Increased productivity due to optimized processes	- Requires significant computing power	
	- Increased efficiency	- Scalability issues	

Note: References for each subfield's advantages and limitations are provided in the References column.

This study has identified several challenges that affect the adoption of AI in the construction industry. These challenges are discussed below:

Cultural Issues and Explainable AI

The construction industry has been slow to adopt new technologies due to the risky and costly nature of construction processes. Traditional methods are preferred over untrusted technologies. To encourage adoption, AI technologies must be usable in different construction projects and tested thoroughly. Additionally, the use of explainable AI (XAI) is crucial to build trust in AI systems. Construction practitioners need to understand how AI systems make decisions, which can be achieved through approaches like local interpretable model-agnostic explanations (LIME) and layer-wise relevance propagation (LRP).

Security

While AI can enhance security and detect intrusions, it is also a target for exploitation by hackers and cybercrimes. Mistakes in construction processes can have significant implications for quality, cost, and time, affecting the overall project plan and compromising worker safety. Mitigation strategies such as adversarial machine learning need to be employed to minimize security risks. Further research is required to address security issues in emerging AI technologies like computer vision and robotics.

Talent Shortage

There is a global shortage of AI engineers with the necessary skills to drive AI developments across industries, including construction. It is challenging to find AI engineers experienced in the construction sector to develop custom solutions for industry-specific problems. Addressing this shortage requires increased investment in STEM education and collaboration between construction experts and AI researchers.

High Initial Costs

The benefits of AI-driven solutions in construction are undeniable. However, the initial costs of implementing AI technologies, such as robotics, can be prohibitively high. Maintenance requirements also need to be considered. This poses a challenge for smaller subcontractors and firms in the construction industry. Determining cost savings and return on investment is crucial in deciding whether to invest in AI technologies. As these technologies become more prevalent, prices are expected to decrease, making them more affordable for smaller firms.

Ethics and Governance

Establishing public trust in AI technologies relies on inclusive, transparent, and agile governance. Ethical considerations are essential to prevent potential dangers and unfair advantages. Regulations should address issues like decision-making in critical situations and ensure fairness in the construction industry. Building ethics into AI systems and implementing AI safety engineering practices are important steps in addressing these challenges.

Computing Power and Internet Connectivity

Construction sites are often remote and lack reliable power, telecommunications, and internet connectivity. This poses a problem for AI tools that rely on these resources, such as robots and site monitoring systems. Real-time computation and communication can be disrupted. Solutions should be sought to ensure efficient operation despite limited connectivity and power interruptions. The emergence of technologies like 4G and 5G communication can help overcome these challenges.

CONCLUSION

Artificial Intelligence (AI) has the potential to revolutionize the construction industry by improving productivity and addressing various challenges. By leveraging the increasing amount of data generated throughout the building lifecycle and combining it with other digital technologies, AI can enhance construction processes. This study reviewed the application of AI technologies in construction, including computer vision, robotics, natural language processing (NLP), machine learning (ML), automated planning and scheduling, knowledge-based systems (KBS), and optimization.

The study employed a qualitative approach by reviewing publication trends for AI and its subfields over the last six decades using databases like SCOPUS, Science Direct, IEEE, and ACM. The findings classified AI subfields into emerging, ripe, and mature fields in construction research. Computer vision, robotics, and NLP were categorized as emerging technologies, while ML, automated planning and scheduling were considered ripe technologies, and KBS and optimization were identified as mature technologies. The study also developed a hype cycle to predict the duration for each subfield to reach maturity.

Although AI technologies have been applied in construction research, the adoption of recent advancements has been relatively slow. For example, the use of deep learning, which can provide more accurate predictions than conventional ML techniques, has not been widely adopted. Additionally, the study identified opportunities and open research issues for AI in construction, considering emerging trends such as Building Information Modeling (BIM), Internet of Things (IoT), quantum computing, augmented reality, cybersecurity, and blockchain.

The study highlighted challenges hindering the adoption of AI in the construction industry and provided recommendations to address them. The information presented in this study can be valuable for researchers and practitioners in the construction industry, helping them understand the potential benefits and barriers of AI implementation. Construction stakeholders, including regulatory bodies, decision-makers, high-skilled workers, and digital enthusiasts, can utilize this information to define a clear pathway for AI implementation and mitigate potential risks.

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