ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN CONSTRUCTION MANAGEMENT: A COMPREHENSIVE REVIEW OF APPLICATIONS, CHALLENGES, AND FUTURE DIRECTIONS

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ABSTRACT

Artificial Intelligence (AI) and Machine Learning (ML) are being continuously reshaped the landscape of construction management, empowering data-driven decision-making, prediction, monitoring, and optimization. The review is based on an integrative literature approach and reviews the applications of AI and ML in cost estimation, planning and scheduling, safety and risk management, progress monitoring, quality control, resource management, contract management and sustainability. AI/ML integration with deep learning, computer vision, Natural Language Processing (NLP), Building Information Modeling (BIM), Internet of Things (IoT), digital twins, and generative AI are also included in the review. The results show that such technologies can help enhance the efficiency of projects, resource management, safety, cost management, time management, and decision-making. The challenges that stem from data quality, interoperability, model accuracy, explainability, cyber security, implementation costs, and skills of the workforce, however, limit their implementation. The future of AI research and development should focus on the integration of multiple systems, such as the BIM–IoT–digital twin system, responsible and explainable AI, and the application of generative AI in intelligent decision-making support systems.

Keywords: Artificial Intelligence (AI); Machine Learning (ML); Construction Management; Digital Construction; Building Information Modeling (BIM); Predictive Analytics.

1. INTRODUCTION

The construction industry plays an important role in economic development but faces several challenges, including cost overruns, project delays, safety risks, resource limitations, and complex project activities [1]. Manual monitoring, relying on historical data and expert judgment are the primary approaches used in traditional construction management, which struggle to deliver prompt and accurate decisions in all cases. So, the use of advanced digital technologies is growing for enhancing the performance of construction projects.

Figure 1: Construction Industry [2]

Artificial Intelligence (AI) and Machine Learning (ML) have proven to be crucial technologies in the field of construction management, driving a new era of intelligent and data-informed construction practices. They are able to process massive amounts of data on the project and provide support for various applications including cost estimation, scheduling, safety management, risk prediction, progress monitoring, quality inspection, and resource optimization [3]. Their ability to connect with other technologies like BIM, IoT, computer vision and digital twins can enhance real-time monitoring and predictive decision-making.

However, the use of AI and ML in the construction industry comes with some drawbacks, including data quality issues, smaller data sets, interoperability problems, shortage of skilled workers, implementation costs, cyber-security concerns, and model reliability. Thus, this review focuses on the significant use of AI and ML in construction management, the major challenges and limitations, and important future research directions for making construction project management more efficient, reliable, and intelligent [4].

1.1. Review Objectives

The main review objectives are:

- To examine the applications of AI and ML in construction management.
- To assess AI/ML technologies and their integration with digital construction.
- To identify challenges, research gaps, and future directions for AI/ML adoption.

2. REVIEW METHODOLOGY

This research is based on an integrative literature review approach to deal with the comprehensive investigation of the role of Artificial Intelligence (AI) and Machine Learning (ML) in Construction Management [5]. Major application areas such as cost estimation, planning and scheduling, safety and risk management, progress monitoring, quality control, resource management, contract management and sustainability were considered in the literature. The review also covered key technologies such as deep learning, computer vision, Natural Language Processing (NLP), BIM, IoT, Digital Twins and Generative AI. The data quality, interoperability, model accuracy, explainability, cybersecurity issues, implementation costs, and workforce issues were given special focus. Last, the findings were compiled to pinpoint the current gaps in the research and future steps towards the successful and sustainable implementation of AI/ML in construction management [6]. The methodology is presented according to the integrative review structure as shown in the sample paper attached.

3. AI AND ML APPLICATIONS IN CONSTRUCTION MANAGEMENT

Artificial Intelligence (AI) and Machine Learning (ML) are being identified as a means to tackle various aspects of construction management and improve decision making in the field, reduce uncertainty and optimize project performance [7]. Historical project data, images, schedules, cost data, sensor data and project documents can be used as input for AI/ML models to detect patterns and make predictions. The applications mentioned in the literature, which are major applications, are cost estimation, planning and scheduling, safety, progress monitoring, quality control, resource management, contract analysis, and sustainability.

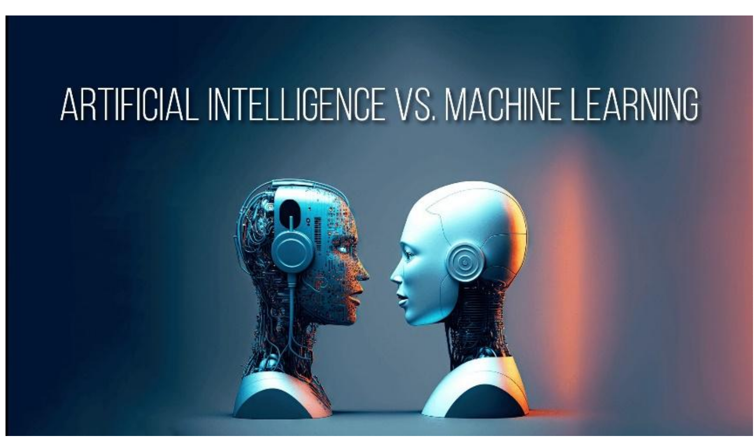

Figure 2: Artificial Intelligence (AI) and Machine Learning (ML) [8]

3.1 Cost Estimation and Prediction

Estimation of construction costs can be achieved using AI and ML based on the historical data of the project, quantities of materials, labour needs, project size, location and other cost-related factors. These variables can be linked to each other in complex ways and machine learning models can predict costs at an early stage. These techniques can also be used on a construction project to help with cost estimation by predicting possible cost escalations due to changes in design, resource requirements, and delays. Hence, AI cost estimation tools can help project managers with better cost control, financial planning, and budgeting.

3.2 Planning and Scheduling

The construction projects need to be planned and scheduled to finish them in the stipulated time. AI and ML can review past project schedules, project duration, resources needed, and project constraints to forecast delays and optimize activity sequencing. Optimization techniques can also determine a set of activities and resources that will shorten the duration of the project. When changes do occur during construction, AI-driven scheduling can give them continual decision support to react better to unexpected delays and disturbances [9].

3.3 Safety and Risk Management

There are a variety of safety risks at construction sites related to people, equipment, materials, and site conditions. AI and ML can be used to assist safety management by detecting potential hazards and predicting high-risk scenarios. Computer-vision solutions can monitor site images and videos to identify unsafe conditions, worker activities and personal protective equipment (PPE) compliance. Historical accident and safety records can also be used with ML models to detect factors that are correlated with higher accident risk.

3.4 Progress Monitoring

The traditional approach to monitoring the progress of construction relies on visits, photos, measurements and regular reports. Several aspects of this process can be automated using AI, computer vision, drones and other digital technologies. Images and videos taken at construction sites can be against planned activities or against BIM models to check the real progress of work [10]. Progress monitoring using Artificial Intelligence can be used to detect delays, monitor activities completed, and give managers more timely information for project control.

3.5 Quality Control and Inspection

AI and ML offer fresh solutions to identify construction defects and enhance quality control. Photographs and videos can be used to detect visible quality issues, such as cracks, surface defects, improper construction, and more, using computer-vision or deep-learning techniques. AI can help minimize reliance on a fully manual inspection, and can detect faults early. Although the inspection results produced by AI can be helpful, it is imperative that these be verified by qualified professionals before they are accepted due to their technical standards and engineering judgement.

3.6 Resource and Productivity Management

Labour, equipment, materials and other resources must be efficiently managed to control construction cost and time. AI and ML can use past productivity, equipment usage, and employee data and project timelines to predict future resource needs. Optimization methods can then be used to more efficiently distribute the resources. AI-based productivity analysis can also help managers determine what factors are driving low productivity and take corrective measures to optimize the use of workforce and equipment.

3.7 Contract and Document Management

Construction projects produce lots of contracts, specifications, reports, correspondence, claims and other documents. These documents can then be processed using NLP, ML and emerging large language models to classify information, highlight clauses, uncover any contractual obligations, and identify risks amongst them. AI can also help with searching, summarizing, and information retrieval in documents, which can save time manual document analysis of documents for manual tasks [11]. While human review is still necessary, for example in contractual and legal matters.

3.8 Sustainability Management

AI and ML can play a role in sustainable construction by studying energy use, material consumption, transportation, waste generation and equipment operation. These technologies can assist in forecasting energy and resource needs and look for ways to cut back on wastes, emissions, and needless resource use. In addition, AI-based optimization can simulate and evaluate different construction options in terms of cost, time, energy use, and environmental impact. In this context, AI and ML can play a role in creating more efficient and environmentally friendly building initiatives.

4. AI/ML TECHNOLOGIES AND INTEGRATION WITH DIGITAL CONSTRUCTION

The development of digital construction has increased the use of Artificial Intelligence (AI) and Machine Learning (ML) technologies for improving project planning, monitoring, analysis, and decision-making. Various AI methods can be applied to various forms of construction data such as numerical data, images, videos, sensor data, BIM models, and project documentation. Combining these technologies with BIM, the Internet of Things, digital twins and generative AI creates a more connected and intelligent way of working in construction management.

4.1 Machine Learning and Deep Learning

Machine Learning (ML) can help computer systems learn patterns from previous construction data and predict and classify data based on those patterns. The cost estimation, delay prediction, productivity analysis and risk assessment can be enabled by ML techniques like decision tree, random forest, support vector machine and artificial neural networks [12]. More advanced type of ML, Deep Learning (DL), is very helpful in analyzing large and complex datasets, especially when analyzing images, videos, and sequential project information.

4.2 Computer Vision

The ability to extract valuable data from images and videos captured from construction sites is made possible by computer vision. It's suitable for worker monitoring, PPE detection, progress tracking, equipment identification, defect detection and safety assessment. Visual data from cameras, drones and mobile devices can be used to analyze data with deep-learning models. The use of computer vision could help to decrease manual inspections and increase the amount of information released more often regarding actual site conditions.

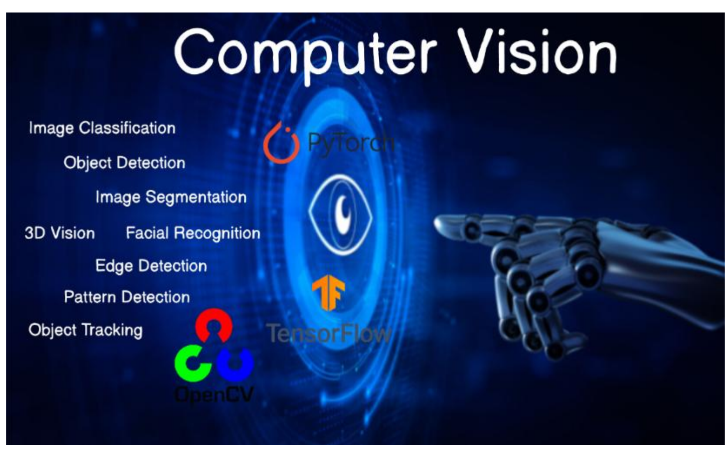

Figure 3: Computer Vision [13]

4.3 Natural Language Processing

Natural Language Processing (NLP) is used to understand and analyse human language using computers. A lot of written information arises in construction projects in the form of contracts, specification, meeting minutes, reports, requests for information and correspondence. Information retrieval, document classification, information extraction, contract-risk identification and summarization of reports are all applications in which NLP can help to retrieve the information from the project.

4.4 BIM and AI Integration

Building Information Modeling (BIM) is a digital representation of building components, geometry, materials and activities. The use of AI in conjunction with BIM can assist with automated quantity take-off, cost forecasting, scheduling, clash risk analysis, progress tracking, and decision-making [14]. AI can also analyze BIM data in conjunction with past project data to pinpoint issues and make forecasts.

4.5 IoT and AI

The Internet of Things (IoT) involves using connected sensors and devices to gather real-time data from construction sites. Many of the parameters of a project can be measured by sensors, including equipment operation, worker location, environmental conditions, material movement, etc. These streams of data can be harnessed by AI and ML to detect out-of-norm conditions, forecast equipment performance issues, monitor productivity, and aid safety management.

4.6 Digital Twins

A digital twin is a digital copy of a physical construction asset or process, which is continually updated, based on the information provided in the physical environment. AI can be leveraged with digital twins for real-time monitoring, predictive analysis, risk identification, progress assessment, and optimization [15]. Digital foundation can be created with BIM, and real-time data can be captured with the use of other sensing technologies and IoT.

Table 1: AI/ML Technologies and Their Applications in Digital Construction [16]

Technology	Main Data Used	Major Construction Applications	Key Benefits
Machine Learning	Cost, schedule, productivity and project records	Cost prediction, delay prediction, risk assessment	Improved prediction and decision-making
Deep Learning	Images, videos and complex datasets	Defect detection, safety monitoring, progress tracking	Automated analysis of complex data
Computer Vision	Site images, videos and drone imagery	PPE detection, progress monitoring, quality inspection	Faster and automated visual inspection
NLP	Contracts, reports and correspondence	Contract analysis, document classification, summarization	Efficient information extraction
BIM + AI	BIM models and project data	Quantity estimation, scheduling, cost and progress analysis	Integrated project decision support
IoT + AI	Sensor and real-time site data	Equipment monitoring, safety and productivity analysis	Real-time monitoring and prediction
Digital Twins	BIM, IoT and operational data	Predictive monitoring, simulation and optimization	Dynamic representation of project conditions

Table 1 shows that every AI/ML technology provides solutions for various types of construction information and management needs. They have their best potential for use when they are integrated, and not used in isolation. When BIM, IoT, computer vision, digital twins, and AI/ML are integrated, they can be used to develop a connected digital construction world where project data is constantly captured, analyzed, and used to inform decisions regarding the management of the project [17].

5. CHALLENGES AND LIMITATIONS OF AI/ML ADOPTION

While AI and ML can provide numerous advantages for construction management, data, technical, financial, and organizational issues impact their adoption. The major limitations are discussed below [18].

- **Data Availability and Quality:** Incomplete and inconsistent data or poor organization of construction data. Insufficient and poor-quality data can negatively impact the trustworthiness of AI/ML models.
- **Data Interoperability:** Different construction software and platforms utilize different data formats and standards. This can make it challenging to incorporate BIM, cost, scheduling and site data.
- **Model Accuracy and Generalization:** AI/ML models developed in one project might not be as accurate or effective in other projects, which can be influenced by different construction conditions. Validation and model updating is therefore needed.
- **Explainability and Trust:** AI models can be complex and may not provide an easy-to-follow explanation of how they make a prediction. Lack of transparency can reduce the confidence of construction professionals in AI-based decisions [19].
- **Cybersecurity and Privacy:** AI systems can process sensitive data related to projects, finances, contracts, and employees. Robust security and privacy protections are essential to protect against unauthorized access and data loss.
- **Cost and Technical Requirements:** Implementing AI can be costly, involving the use of expensive software, sensors, computing infrastructure, and skilled professionals. It can be challenging for smaller construction companies to meet these requirements.

Table 2: Summary of Reviewed Literature on Artificial Intelligence and Emerging Digital Technologies [20]

Reference	Focus of Study	Key Findings
Himeur et al. (2023) [21]	AI and big data analytics in building automation and management	AI and big data improved building automation, monitoring, and management, but implementation challenges remained.
Lu (2019) [22]	Evolution, models, applications, and future trends of AI	AI evolved as an important technology for intelligent analysis, prediction, automation, and decision-making.
Habbal et al. (2024) [23]	AI Trust, Risk, and Security Management (AI TRiSM)	Emphasized trust, risk, security, and reliability as essential for responsible AI implementation.
Chengoden et al. (2023) [24]	Metaverse applications, challenges, and future directions in healthcare	Highlighted the potential of emerging digital technologies while identifying technological, security, and implementation challenges.

6. FUTURE DIRECTIONS AND RESEARCH GAPS

AI and ML applications in construction management are evolving rapidly, yet some areas still need more research to get to a dependable and useful level of implementation [25]. Future studies will involve further development of data integration, model transparency, automation, and collaboration among AI systems and construction practitioners [26].

- **Multimodal AI:** AI can bring together various types of construction data, including text, images, videos, BIM models, sensor data, and project records. Multimodal AI has the potential to offer higher level analysis and decision-making in construction operations [27].
- **Explainable and Responsible AI:** The future AI models should present understandable reasons to their predictions and recommendations [28]. The scope of research should include explainability, transparency, fairness, privacy, safety and accountability, to build trust in AI-driven construction decisions.
- **BIM–IoT–Digital Twin Integration:** The connection between BIM, IoT, digital twin and AI can produce dynamic construction environments that are constantly updated [29]. Going forward, systems need to be designed that integrate real-time project data with AI predictions and optimizations to improve project monitoring and control.
- **Generative AI in Construction:** Generative AI and Large Language Models (LLMs) can be used to generate reports, analyze contracts, summarize documents, retrieve information, and manage project knowledge. Future studies should be more precise, source verified, secure and construction specific [30].

- **Reinforcement Learning and Autonomous Decision Support:** RL can be used to aid in dynamic construction decisions like scheduling, resource allocation, logistics and disruption management. More studies are required to guarantee that such systems are dependable and secure prior to being applied in actual construction work.

7. CONCLUSION

The current review shows that Artificial Intelligence (AI) and Machine Learning (ML) hold significant promise for transforming construction management by leveraging these technologies to boost cost estimation accuracy, scheduling efficiency, safety management, progress tracking, quality oversight, resource optimization, contract administration, and sustainability efforts. AI/ML can also complement BIM, IoT, computer vision, digital twins, and generative AI to aid in real-time monitoring and data-driven decision-making. Problems of data quality, interoperability, model reliability, model explainability, cybersecurity, implementation costs and workforce skills are significant obstacles to effective adoption. Applying multimodal AI, responsible AI, explainable AI, integration of BIM – IoT – digital twin, generative AI, and intelligent decision support systems should be the focus of future research. In conclusion, sustainable adoption of AI/ML in the construction industry will require the support of reliable data, suitable technological infrastructure, competent professionals, and successful human–AI collaboration, which will help build the future of efficient, predictive, integrated, and intelligent project management.

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