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Enhancing Construction Safety Performance Through Artificial Intelligence: A Systematic Review

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Abstract

The construction industry is still one of the most dangerous sectors globally because of its dynamic working environment, the employment of heavy machinery, and the complexity of operational processes. Traditional safety management methods are largely dependent on manual monitoring and reactive measures, which are not always effective for accident prevention. In recent years, artificial intelligence (AI) has been recognized as a revolutionary technology in construction safety, with capabilities such as predictive risk analysis, real-time hazard detection, and automated safety management systems. This paper presents a review of the use of AI technologies in improving construction safety performance, with a focus on major AI-enabled tools such as computer vision, wearable technology, unmanned aerial vehicles (drones), robotics, and Building Information Modelling (BIM). It also discusses the challenges, opportunities, and future research avenues in the use of AI-enabled safety systems in the construction industry. The results show that AI-enabled safety systems play a significant role in minimizing workplace accidents, improving regulatory compliance, and optimizing overall operational efficiency. The paper highlights the increasing need for AI integration in promoting proactive safety management systems and creating a safe working environment in the construction industry.

Keywords: Artificial intelligence, construction safety, predictive analytics, wearable technology, BIM, computer vision, risk management

INTRODUCTION

The construction industry is crucial for economic development as it supports infrastructure development, urbanization, and industrialization. However, the industry continues to experience serious challenges related to occupational health and safety. Construction sites are inherently complex and dynamic, with constantly varying working conditions, heavy machinery use, and concurrent performance of multiple activities. These factors contribute to a high rate of workplace accidents, injuries, and fatalities, making the construction industry one of the most dangerous industries worldwide. Therefore, worker safety is of utmost importance to all stakeholders in the industry.

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The conventional construction health and safety management system is mainly based on manual supervision, inspection, and regulatory compliance. Although these systems have helped improve health and safety performance over the years, they are mainly reactive, addressing health and safety issues only after they have occurred. Manual monitoring systems are mainly time-consuming, prone to human error, and incapable of real-time risk detection. Additionally, the growing complexity of modern construction projects, with the need for fast-track construction, has further emphasized the need for more efficient and proactive health and safety

management systems. Consequently, there is an increasing need for the application of sophisticated technological solutions that can predict, detect, and counter safety risks before accidents happen.

Recently, artificial intelligence (AI) has been identified as a revolutionary technology with enormous potential for improving the management of construction site safety. AI can be defined as the development of intelligent systems that can perform tasks that are typically the domain of human intelligence, including learning, problem-solving, pattern recognition, and decision-making. By utilizing large amounts of data, AI-based systems can analyze patterns, predict possible dangers, and assist in making rational decisions. The application of AI technologies in construction safety has made it possible to move from a reactive to a proactive approach in managing construction site safety, thus improving accident prevention and construction site performance.

One of the most important applications of AI in construction safety is predictive risk analysis. AI systems can analyze past accident data, environmental factors, and working practices to predict possible safety risks. Machine learning algorithms, for example, can identify patterns related to unsafe working practices and alert project managers and safety managers to take preventive measures. This predictive ability enables organizations to take preventive action and allocate resources to avoid exposure to safety risks. Thus, predictive systems developed using AI can provide a systematic approach to safety management.

Another critical use of AI in construction safety is computer vision technology. Computer vision technology uses image recognition and deep learning algorithms to automatically monitor construction sites using cameras and sensors. Technology is capable of identifying dangerous behaviors, the lack of personal protective equipment, and monitoring workers' movements in real time. This technology is useful for enhancing construction site surveillance and minimizing the need for manual site inspections. Additionally, computer vision technology can enhance hazard detection by identifying dangerous situations, such as unstable structures and unsafe working positions, allowing for immediate corrective measures.

Wearable technology is another critical technology for AI-based construction safety management. Wearable technologies, such as smart helmets, safety vests, and biometric sensors, allow for the continuous monitoring of workers' physical status and environmental exposure. AI-based wearable technology can monitor vital signs, fatigue, and exposure to hazardous materials and extreme temperatures. This technology is useful for providing real-time information on the physical status and safety of workers, thus allowing for early intervention and prevention of occupational injuries. Additionally, the technology is useful for enhancing communication and coordination at construction sites, thus allowing for safety.

The adoption of unmanned aerial vehicles, also known as drones, has further widened the horizon of AI applications in construction safety. AI-enabled drones can perform site inspections, monitor dangerous areas, and analyze structural conditions without putting workers at risk. They offer end-to-end visual information that helps in risk analysis, construction monitoring, and safety analysis. By enabling remote site inspection and data collection, drones minimize the need for workers to work in a potentially dangerous environment, thus improving overall safety performance.

Robotics is another evolving field that helps improve safety in construction operations. AI-enabled robots can undertake dangerous construction tasks, such as demolition, material transport, and inspection work, in high-risk environments. By minimizing the risk of accidents and improving efficiency, robotics improves safety performance. The application of robotics technology also helps maintain precision and consistency in construction activities, which further helps improve safety performance.

Another technology that has been increasingly integrated with AI is Building Information Modelling (BIM), which aims to improve construction safety management. BIM is a digital model that represents the physical and functional characteristics of construction projects. When integrated with AI, BIM can be used to simulate possible safety risks, detect design-related safety hazards, and assist in safety planning throughout the construction process. The integration of BIM and AI enables improved decision-making, collaboration between construction stakeholders, and a proactive approach to risk management.

Despite the numerous benefits associated with the use of AI-based safety technology, several challenges must be addressed to ensure that the technology is widely adopted in the construction industry. These include high implementation costs, data privacy issues, and the need for qualified personnel to manage AI technologies. Additionally, resistance to technological change and the absence of standardized frameworks for AI integration may impede the adoption of AI technology, especially in developing countries like India.

However, the increasing focus on digital transformation and innovation offers great opportunities for the development of AI technology in construction safety. Further research and development, as well as favorable government policies, can facilitate the integration of AI technology. Future studies are expected to focus on improving accuracy, enhancing real-time monitoring, and developing cost-effective technology.

In this regard, the purpose of this study is to discuss the significance of AI technologies in enhancing the safety performance of the construction industry by analyzing the most significant AI-enabled tools, such as computer vision, wearable technology, drones, robotics, and BIM. This study also discusses the challenges, opportunities, and future research avenues associated with the adoption of AI technology in the safety management of the construction industry. By identifying the effects of AI-enabled safety systems on the reduction of accidents, compliance with regulations, and efficiency, this study will help develop the existing knowledge base on technology-enabled safety management in the construction industry. Finally, the adoption of AI technologies has the potential to revolutionize construction safety practices by allowing proactive safety management and promoting a safe construction environment.

LITERATURE REVIEW

AI has been identified as a revolutionary technology in the construction sector, particularly in improving safety management practices. The growing complexity of construction environments, the number of accidents, and the inefficacy of traditional safety monitoring systems have led to the rapid development and implementation of AI-based safety management systems. Recent systematic reviews indicate that AI-based technologies have been shown to improve hazard identification, risk assessment, and worker monitoring capabilities compared to traditional safety management systems [1, 2].

Studies have indicated that AI can be used for predictive, proactive, and automated safety management, and the construction industry can move from a reactive approach to accident management to a proactive approach to safety management [3, 4]. The combination of machine learning, computer vision, and data analytics capabilities of AI enables construction companies to process large amounts of data and make informed decisions [5].

One of the significant uses of AI in construction safety is monitoring workers and managing risks. AI-based systems make it easier to monitor workers' activities in real time, detect dangerous behavior, and detect dangerous working conditions [6]. These systems employ sensors, cameras, and wearable devices to gather and analyze safety data [7].

According to Pandit (2025), wearable AI technology is critical for monitoring workers' health conditions, fatigue levels, and exposure to dangerous environments [8]. Gudibandi (2025) also pointed

out that AI technology is used in smart construction sites for predictive risk analysis and safety optimization. This technology helps minimize human error and improve safety regulation compliance [8, 9, 10].

Samadder et al. (2025) concluded that AI-based risk management systems improve safety performance by detecting possible risks before they occur. AI-enhanced safety management systems also improve the accuracy of hazard prediction and allow for quick responses to emergencies [11].

Computer vision and deep learning technologies are important for enhancing safety at construction sites. This technology allows for automated construction activity monitoring through image and video processing. Lee and Lee (2023) proposed a computer vision-based safety management system that can automatically identify unsafe worker behaviors and safety violations in real time [12].

Zhang (2021) demonstrated the efficiency of machine vision technology in construction activity monitoring and accident prevention. Smart vision technologies can also be used for object detection, worker tracking, and personal protective equipment (PPE) safety monitoring [13, 14].

Rabbi and Jeelani (2024) further classified AI applications in construction safety into text-based, vision-based, and audio-based systems. Vision-based AI systems are the most efficient in hazard detection, whereas text- and audio-based AI applications assist in safety communication and reporting [15].

Data-driven AI algorithms play a major role in enhancing safety during construction. Liang et al. (2024) explained the application of data-driven models in the operation of construction machinery, emphasizing their potential to improve operational safety and minimize accidents caused by machinery [16]. Likewise, Zheng et al. (2023) illustrated how data-driven intelligent technologies improve the performance of machinery and ensure safety for workers [17].

Min and Huang (2024) introduced intelligent safety management systems based on AI-driven decision-making models that improve risk forecasting and accident prevention. Chen et al. (2024) argued that AI helps ensure the safety of infrastructure construction by applying predictive analytics, real-time monitoring, and automated decision-making [18].

Intelligent systems have the potential to manage construction operations more effectively by improving safety planning, risk analysis, and resource allocation.

The development of Construction 4.0 has increased the adoption of AI and digital technologies for safety management. Digital technologies such as BIM, the Internet of Things (IoT), and smart sensors improve safety monitoring and risk management activities [2].

According to Făgărăşian (2025), AI-based digital systems significantly enhance workplace safety by minimizing manual supervision and improving monitoring efficiency. Likewise, Baduge et al. (2022) argued that smart construction technologies make it possible to conduct automated safety inspections and instantaneous danger identification [19, 13].

The adoption of digital platforms also enhances safety communication, recording, and tracking, resulting in improved safety performance in construction projects [20].

Despite these benefits, some challenges hinder the adoption of AI technology in construction safety. These include the cost of implementation, lack of technical knowledge, data privacy issues, and resistance to change [15, 3].

The availability and quality of data also influence the performance of AI systems. For AI to make predictions, it requires a large amount of data, which may not be available in the construction sector [5]. There are also issues with integrating AI technology into existing safety management systems [4].

According to the literature, several research gaps have been identified in AI-based construction safety management. First, most research is concerned with technological advancement and not implementation [1]. Second, there is a lack of research on the combination of various AI technologies into one safety management system.

Future research should aim at:

- Enhancing the reliability and accuracy of AI models
- Designing cost-effective safety monitoring systems
- Combining AI technology with BIM and IoT systems
- Considering ethical and data privacy issues
- Assessing the outcome of implementation

In addition, an interdisciplinary approach that incorporates AI, human factors engineering, and safety management principles is required to leverage the benefits of AI in construction safety.

AI TECHNOLOGIES USED IN CONSTRUCTION SAFETY

Computer Vision and Real-Time Hazard Detection

Computer vision is one of the most commonly used AI technologies in construction safety management. It uses cameras, sensors, and machine learning algorithms to monitor construction sites in real time, making it possible to automatically detect dangerous conditions and unsafe worker behavior. By analyzing visual data obtained from surveillance cameras, computer vision algorithms detect patterns, identify objects, and analyze worker activity to enhance safety compliance (Figure 1).

The main applications of computer vision technology in construction safety include PPE compliance detection, unsafe behavior observation, fall hazard detection, restricted area observation, and equipment misuse detection. Computer vision technology can automatically detect whether construction workers are wearing safety helmets, gloves, or high-visibility vests, and it can also detect dangerous behavior such as improper equipment use or restricted area entry (Figure 2).

Figure 1. Surveillance.

Figure 2. (a) and (b) Detecting the errors.

Figure 3. Monitoring.

The AI-based monitoring system also enables real-time notifications to site managers and safety officers, allowing them to take corrective measures immediately. The AI-based monitoring system also reduces the need for manual monitoring and improves the accuracy of hazard detection. Research also suggests that machine vision systems can detect safety hazards with an accuracy rate of 93%, thus reducing safety incidents (Figure 3).

Wearable Safety Devices

Another major innovation in construction safety technology is the use of AI-enabled wearable devices. Wearable technology constantly tracks the physical condition of workers and their exposure to the environment, offering real-time information that enables proactive safety measures. By combining sensors and AI, wearable technology can identify possible dangers associated with the physical condition of workers, fatigue, and environmental factors (Figure 4).

Examples of wearable safety technology include smart helmets that can detect falls, GPS tracking devices that track the location of workers, biometric sensors that track vital signs such as heart rate and body temperature, fatigue sensors, and smart safety vests equipped with environmental sensors. Wearable technology allows for constant tracking of worker movement, physical condition, and exposure to dangerous environments (Figure 5).

Wearable technology improves safety compliance by offering early warnings of possible health dangers and exposure to hazardous environments. For example, AI technology can detect signs of fatigue and stress and warn supervisors before accidents occur. Research indicates that wearable safety technology can improve safety compliance by over 22%, confirming its effectiveness in reducing workplace injuries and improving construction site safety performance, as shown in Figure 6.

Figure 4. Helmet with sensors.

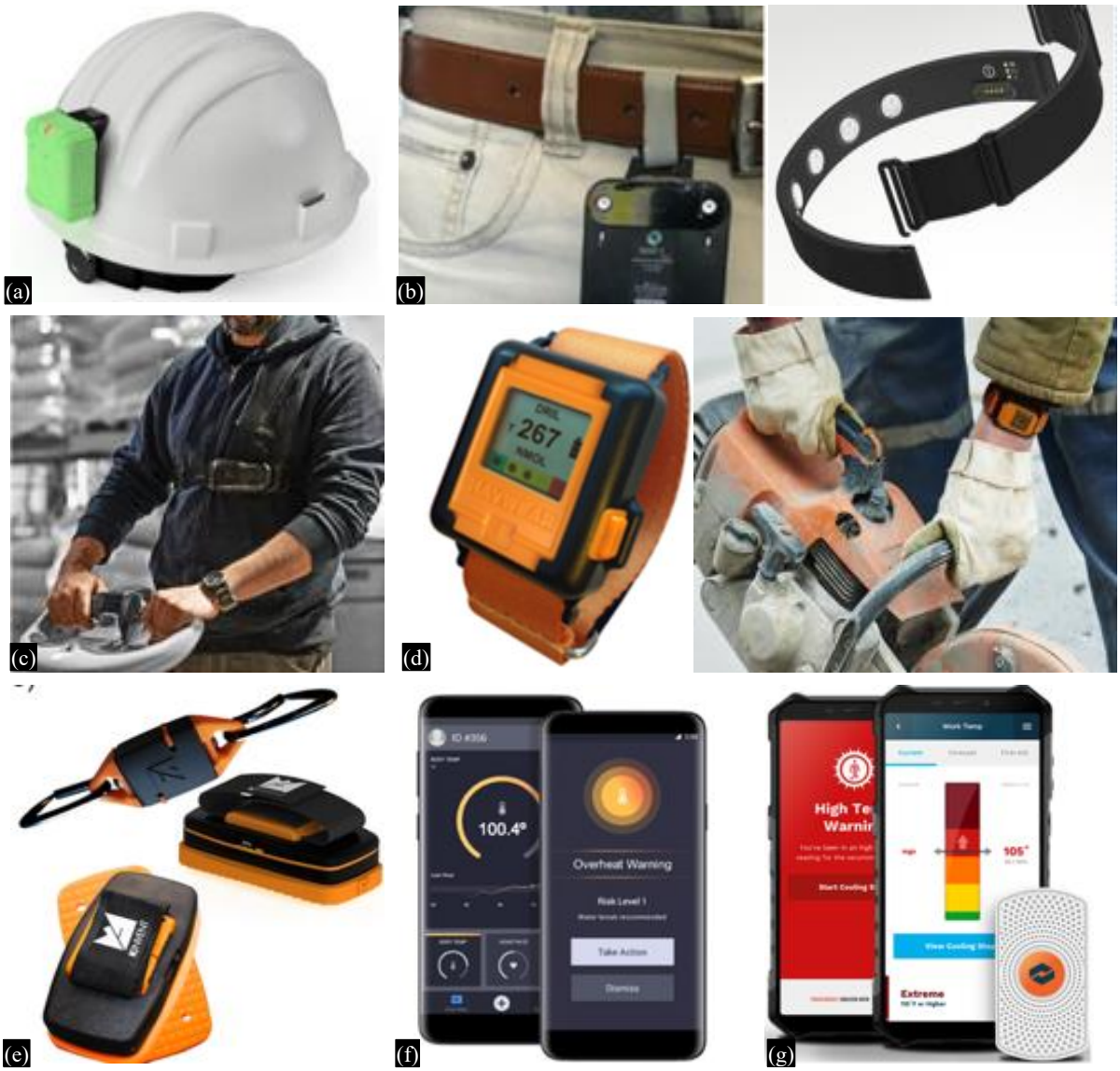

Figure 5. (a) to (f) Different types of wearables.

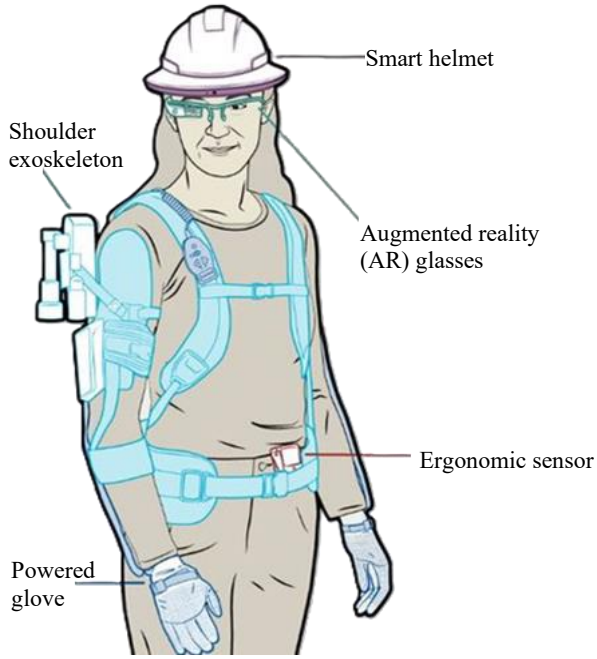

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Figure 6. Indicating AI safety measures.

Figure 7. Drone at the site.

Drones and Robotics in Safety Inspection

AI-driven drones and robots have greatly enhanced safety inspections and hazard management at construction sites. These systems perform automated site inspections, track hazardous areas, and undertake dangerous operations without putting workers at risk. Drones and robots, with their advanced sensors, imaging capabilities, and AI-driven analytics, improve safety inspection and efficiency at construction sites Figure 7.

The main uses of drones and robots in construction are site surveillance and aerial inspection, structural risk analysis, identification of hazards in high-risk or difficult-to-access areas, autonomous safety inspections, and material handling automation. Drones offer high-resolution visual information and real-time monitoring of construction activities, allowing for the quick detection of unsafe conditions, such as structural damage or unsafe working practices (Figure 8).

Compared to conventional safety inspection methods, drones offer faster, more accurate, and more economical safety inspections. Likewise, robots can undertake dangerous operations, such as demolition, confined space inspection, and handling heavy materials. These technologies improve the efficiency of risk detection, minimize human exposure to hazardous environments, and help create a safe construction environment (Figure 9).

Predictive Analytics and Risk Assessment

Predictive analytics is an AI-based approach that relies on data analysis and machine learning algorithms to predict possible safety risks in projects based on past data. Predictive analytics helps organizations detect safety risks by analyzing patterns of accidents, worker behavior, and environmental factors (Figure 10).

The most important advantages of predictive analytics in construction safety are accident, worker risk, weather, and equipment failure predictions. Predictive analytics helps project managers make proactive decisions by identifying risky activities, allocating safety resources, and taking safety actions (Figure 11).

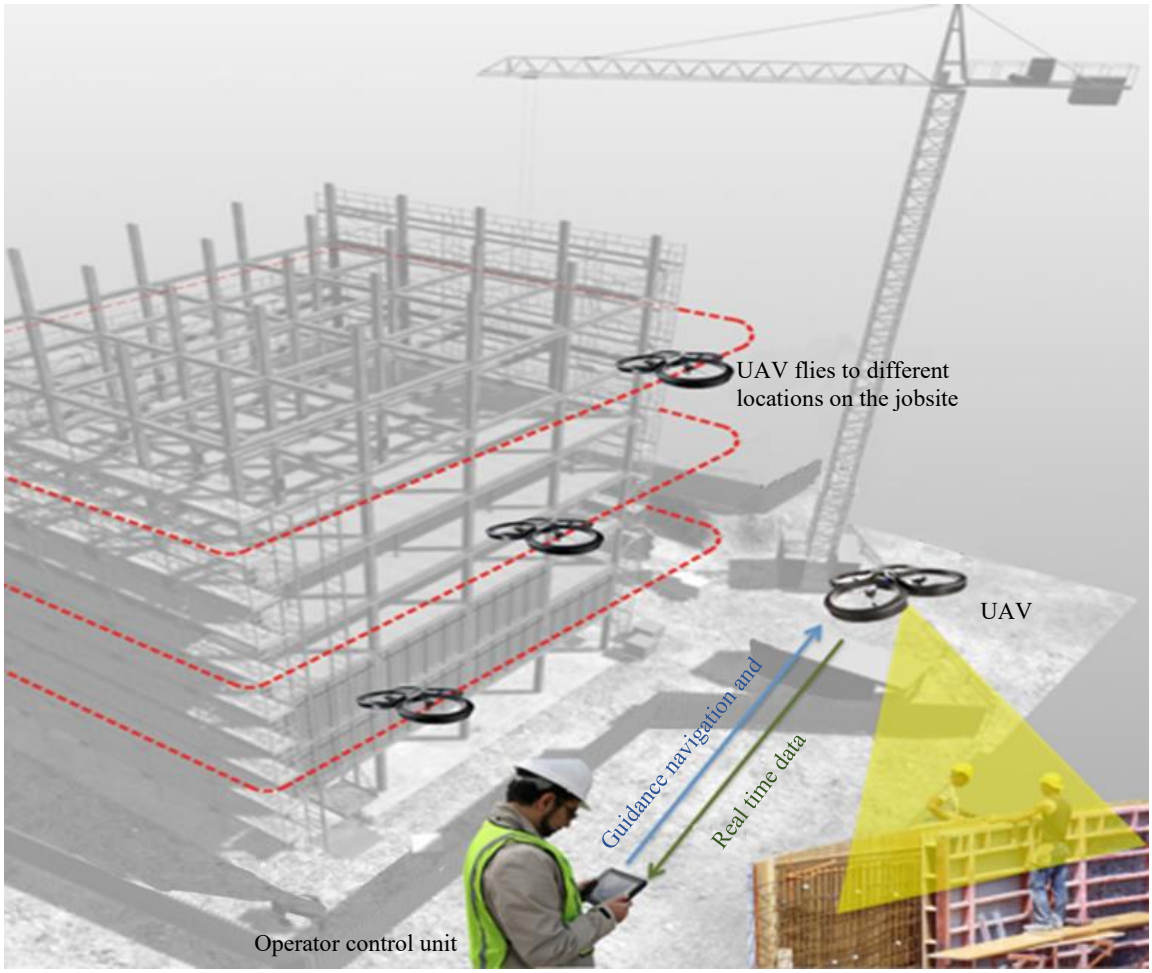

Figure 8. Analysis detection.

Figure 9. Robotics with AI.

Figure 10. Analysis.

Predictive safety analytics is an effective method that minimizes accidents by detecting risk patterns and taking preventive measures before accidents occur. Predictive analytics is a paradigm shift from reactive safety management to proactive safety culture, and hence, it improves construction safety performance.

Building Information Modelling and AI Integration

The integration of AI and BIM improves construction safety planning through digital simulation and advanced visualization tools. BIM is a digital model of construction projects that facilitates the analysis of design, planning, and operational processes. The integration of BIM and AI enables the use of automated hazard identification and predictive safety analyses.

The key applications of AI-integrated BIM include hazard simulation, design-phase safety planning, risk visualization, and maintenance planning. These applications enable project participants to simulate possible safety risks, analyze alternative design options, and undertake preventive actions before actual construction work commences.

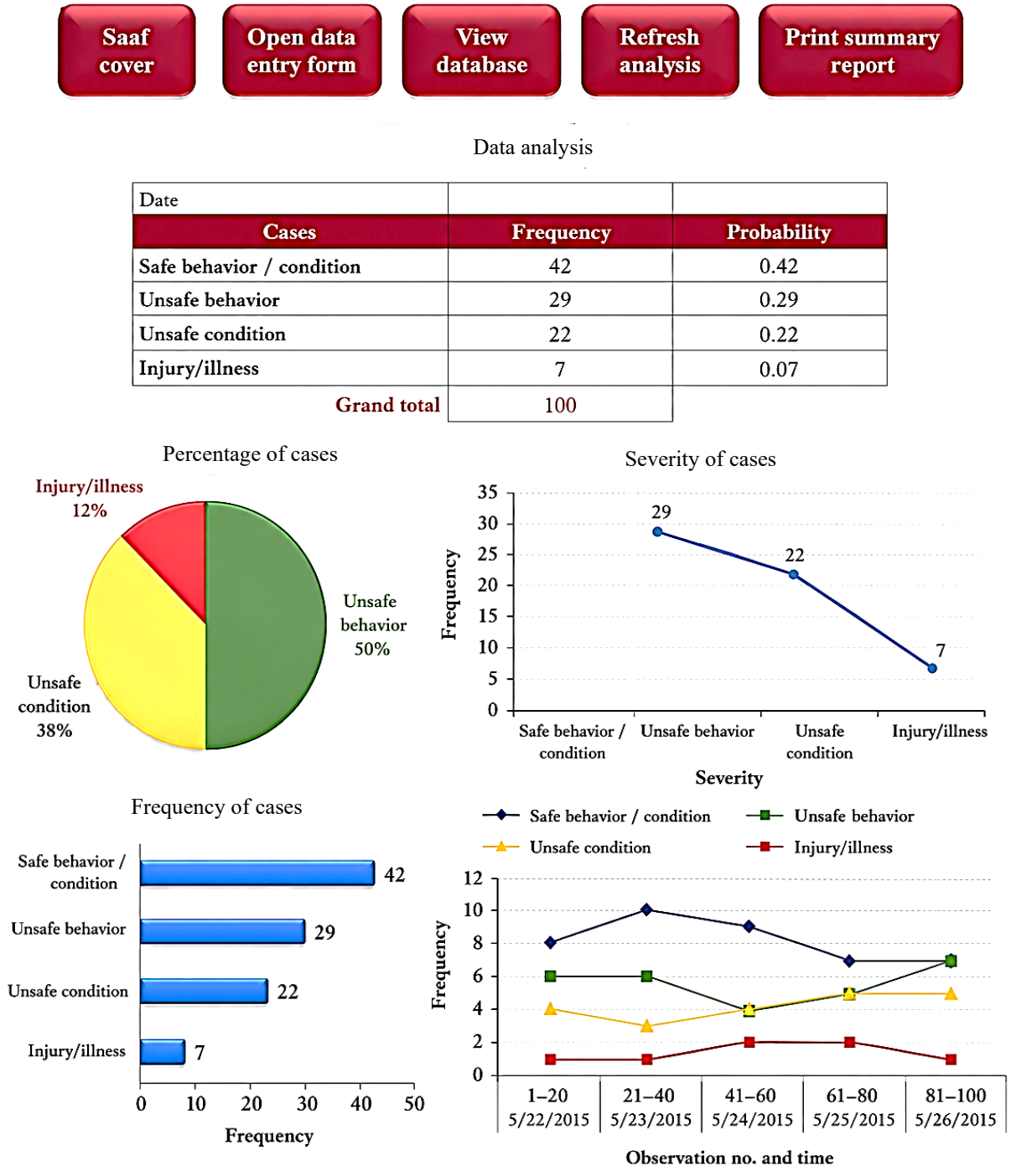

Figure 11. Analysis report.

The integration of AI and BIM improves operational efficiency by optimizing project coordination, minimizing design-related risks, and enabling proactive safety management. Therefore, AI-based BIM applications are essential for promoting digital transformation and improving safety performance in the construction sector (Figure 12).

BENEFITS OF AI IN CONSTRUCTION SAFETY

Reduction in Accidents

One of the most important advantages of AI in construction safety is the reduction in workplace accidents.

AI-based monitoring systems enable continuous monitoring of construction sites, which helps in the early detection of dangerous situations and construction safety violations. Using computer vision and predictive analytics, AI systems analyze data to identify potential hazards and predict the occurrence of accidents. This approach helps in taking preventive measures before an accident occurs, which reduces the number of injuries and improves the performance of construction site safety. Continuous monitoring also reduces human error in manual monitoring, as shown in Figure 13

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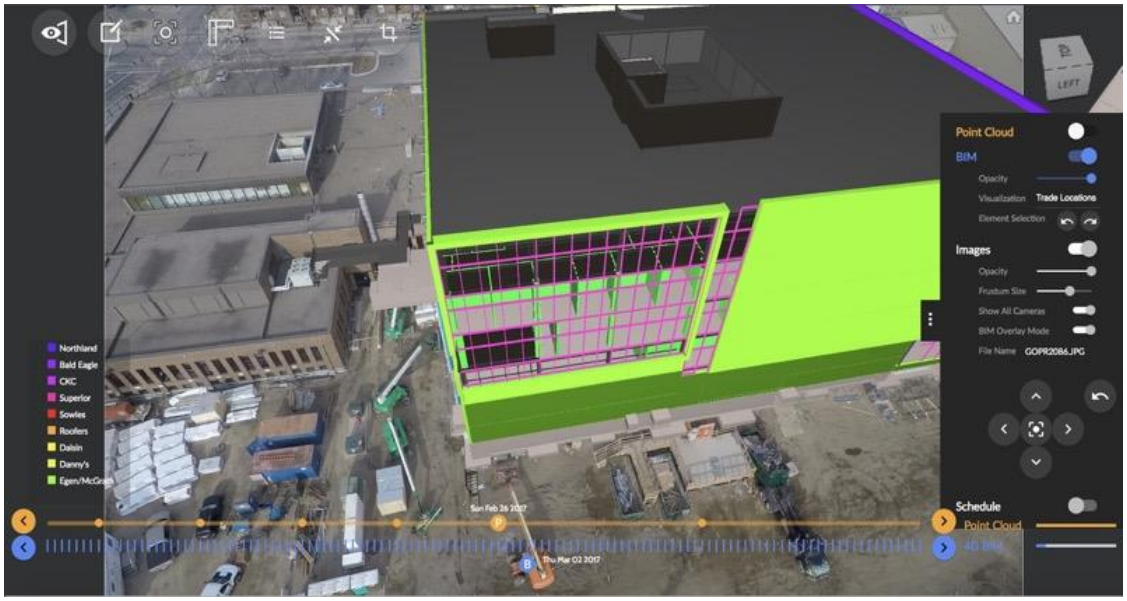

Figure 12. BIM with AI.

Figure 13. Detecting the problems.

Improved Safety Compliance

Safety monitoring and reporting systems using AI technology can greatly enhance safety standards and regulatory compliance. These systems can automatically check if employees are following safety guidelines, such as the use of PPE and operating procedures. There are automated reporting systems that can accurately record safety performance, allowing organizations to be compliant with regulations and improve safety accountability. AI technology can therefore help improve safety culture and performance in a construction setting by reducing non-compliance with safety guidelines (Figure 14).

Faster Incident Response

AI technologies improve emergency response in the following ways: real-time monitoring systems provide instant notifications whenever unsafe conditions or accidents are detected, and safety personnel can immediately respond to the situation. AI-assisted wearable devices are also capable of sending information about the location and health status of workers, which helps in quick medical response in case of an emergency. This increases the efficiency of emergency responses at construction sites, as shown in Figure 15.

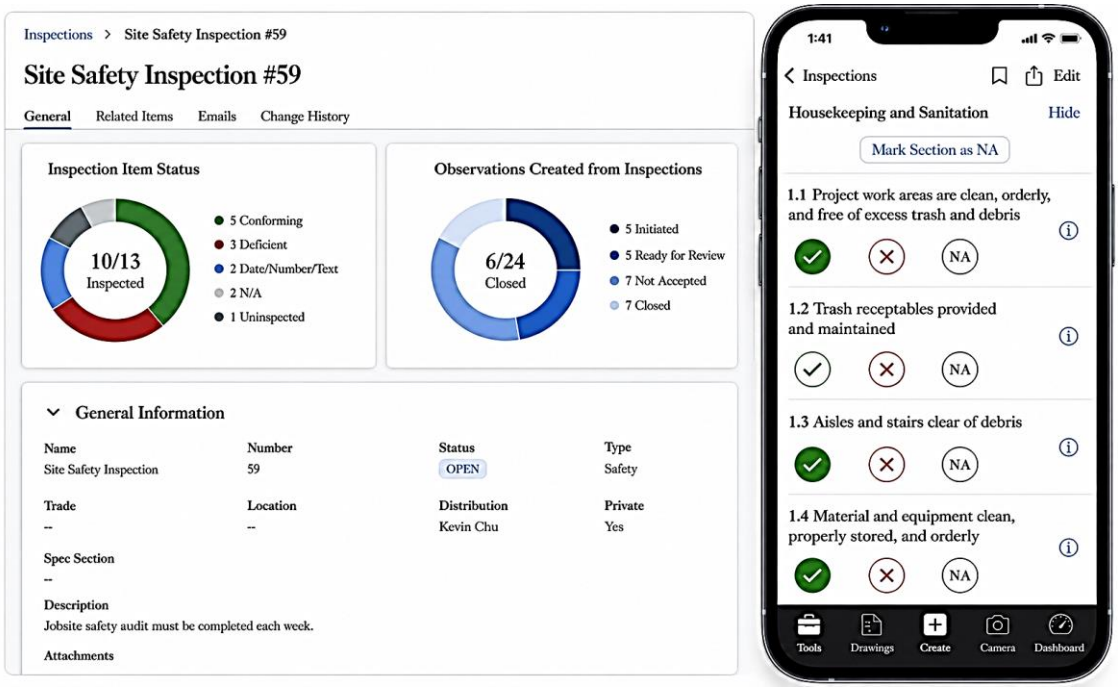

Figure 14. Safety measures.

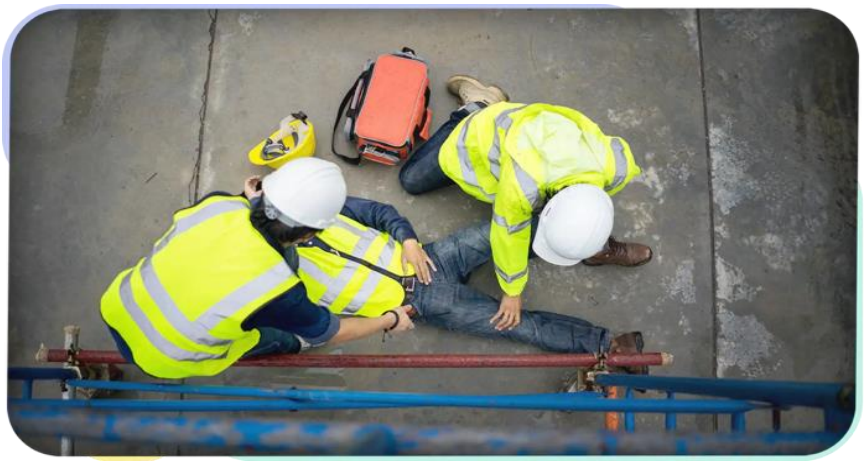

Figure 15. Safety measures with AI.

Enhanced Productivity

The deployment of AI-powered safety systems helps improve productivity by ensuring a safe and organized working environment. With a reduced risk of workplace accidents, employees can work more efficiently with fewer interruptions resulting from workplace accidents or safety infractions, thereby increasing productivity. AI systems help optimize safety monitoring processes, minimize downtime, and improve workflow coordination. Additionally, a safe working environment boosts employee confidence and performance, leading to improved efficiency and project results (Figure 16).

Cost Reduction

The adoption of AI technology in construction safety practices has also resulted in significant cost savings. This is because AI technology reduces workplace accidents, which, in turn, results in lower costs related to medical treatment, compensation, and legal liability. Predictive maintenance and equipment monitoring also reduce machine failures and repair costs, whereas enhanced safety compliance can lead to lower insurance costs. The prevention of accidents and disruptions also improves the efficiency of construction projects, which in turn results in cost savings for construction organizations (Figure 17).

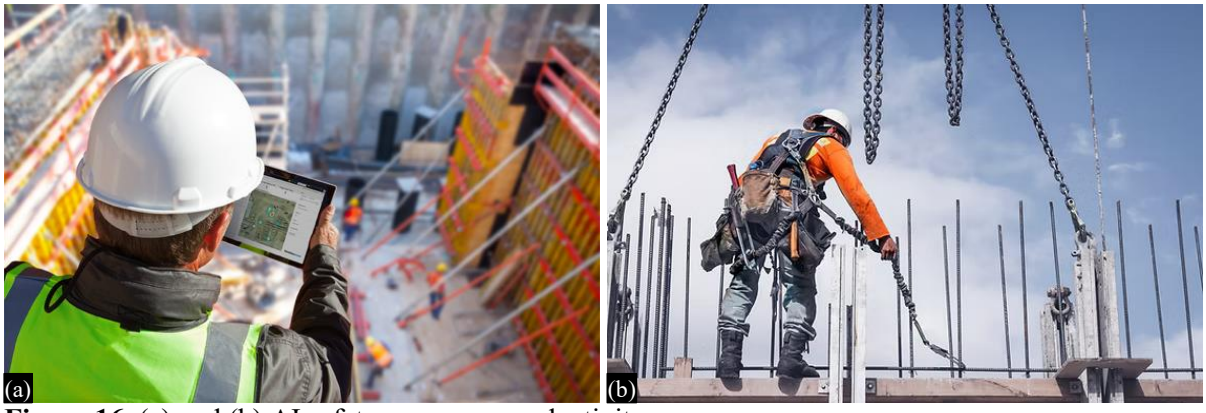

Figure 16. (a) and (b) AI safety measures productivity.

Figure 17. Cost reduction.

CHALLENGES AND LIMITATIONS OF AI IN CONSTRUCTION SAFETY

Although the benefits of AI in enhancing construction safety are immense, some challenges and limitations impede its adoption and implementation in the construction sector.

High Implementation Costs

The implementation of AI technology in the construction sector for construction safety purposes requires heavy investment in terms of money and time. The use of computer vision technology, wearable technology, drones, and AI-based monitoring systems requires a large initial investment, which might hinder their adoption, especially in the case of small- and medium-scale construction companies.

Data Privacy and Ethical Concerns

AI-based safety systems are highly dependent on the continuous collection of data, such as video monitoring, location tracking of employees, and biometric data. These issues can lead to concerns about employee privacy, data ownership, and ethical data use. The lack of clear regulatory frameworks on data protection in a construction setting may lead to resistance from employees and trade unions against technology acceptance.

Lack of Skilled Workforce

For the effective implementation of AI technology, professionals who can develop, operate, and maintain intelligent systems are required. However, the construction industry is often challenged by a lack of professionals with skills in data analytics, machine learning, and digital technology. This is a major hindrance to the implementation of AI technology and the use of advanced safety management systems in the construction industry.

Integration with Existing Systems

Construction companies often rely on conventional safety management approaches and systems. The integration of AI technology into existing work processes, project management systems, and operations can be technically challenging and time-consuming. There are interoperability problems and a lack of standardized frameworks for AI implementation in the medical field.

Reliability and Technical Limitations

AI systems depend on data quality and algorithmic accuracy. Inaccurate data, sensor failures, and environmental factors such as poor lighting, weather conditions, and site variability can affect system performance. False alarms or incorrect risk predictions may reduce user trust and limit the effectiveness of AI-driven safety solutions in the workplace.

Resistance to Technological Change

The construction industry has been sluggish in embracing digital technology. Organizational culture, lack of awareness, and resistance to change have been some of the factors that have contributed to the slow adoption of digital technology in the construction industry. Employees and employers may be resistant to the use of automated systems or may view AI technology as being complex.

FUTURE RESEARCH DIRECTIONS

The fast-paced development of AI technology offers great opportunities for further research and development in construction safety management. Future research should aim to overcome existing limitations and improve the efficiency, availability, and accuracy of AI-based safety systems.

Development of Cost-Effective AI Solutions

Future studies should focus on developing cost-effective AI technology that can be applied by small- and medium-sized construction companies. Affordable sensors, cost-effective AI platforms, and cloud-based safety monitoring systems can improve accessibility and encourage widespread adoption in industry.

Integration of AI with Emerging Technologies

However, further research is required to integrate AI with new and emerging technologies, such as IoT, digital twins, augmented reality, and robotics. The integration of these technologies can improve the safety performance and efficiency of operations.

Improvement of Predictive Models

Future studies should focus on improving the accuracy and reliability of AI predictive models for accident prevention. This can be achieved by improving machine learning algorithms using large-scale data and developing sophisticated risk prediction models that consider complex construction site conditions and human factors.

Human–AI Collaboration in Safety Management

There is an emerging need to investigate the effectiveness of human–AI system collaboration in safety management. Future research should focus on how AI technologies can be used to facilitate decision-making without replacing human judgment so that intelligent systems work in harmony with the operations of the workforce.

Standardization and Regulatory Frameworks

Research should focus on developing guidelines and regulatory frameworks for implementing AI in the construction industry for safety purposes. This will help develop standards regarding data privacy, reliability, and ethical use of AI technologies.

AI Adoption in Developing Countries

Most of the existing literature is concerned with technologically advanced areas, and very few studies have been conducted on AI adoption in developing economies such as India. Future studies should examine the challenges and issues related to AI adoption in countries such as India, where construction activities are growing rapidly.

Long-Term Impact Assessment

Further empirical studies are required to evaluate the long-term effectiveness of AI technologies in reducing accidents, improving safety culture, and enhancing organizational performance. Longitudinal research can provide deeper insights into the sustainability and practical impact of AI-driven safety management systems.

CONCLUSION

The construction sector has continued to face major safety issues owing to the complex and dynamic nature of its working environment. The conventional safety management system, which mainly involves manual monitoring and reactive measures, has proved ineffective in accident prevention and risk control. The development of AI has presented revolutionary opportunities for improving construction safety through predictive risk analysis, real-time hazard identification, and automated safety management systems. This paper has investigated the application of AI technology in improving construction safety performance through a discussion of major applications such as computer vision technology, wearable safety technology, drones, robotics, predictive analytics, and BIM integration. The applications mentioned above play a role in proactive safety management through continuous monitoring of construction sites, hazard identification, and decision support. The results show that AI-based safety technology is highly effective in minimizing workplace accidents, improving safety compliance, optimizing incident response, maximizing productivity, and minimizing operational costs. However, the paper also points out some of the challenges that currently hinder the adoption of AI in construction safety, such as the high cost of implementation, data privacy issues, and the lack of qualified personnel. Overcoming these challenges will require the collective efforts of all stakeholders in the construction industry, including policymakers and researchers. Future studies should aim at improving the predictive capabilities of the models, combining AI with other emerging technologies, and investigating the long-term effects of AI-based safety systems in the construction industry,

especially in developing countries. In conclusion, the adoption of AI technologies is a crucial step towards the advancement of proactive safety management in the construction industry. The future of construction safety management will be shaped by the continued development of AI-based safety systems.

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