REVIEW

AUTOMATION TECHNOLOGIES IN CONSTRUCTION SAFETY MANAGEMENT: A SYSTEMATIC REVIEW

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ABSTRACT

PURPOSE: The aim of this paper is to present a systematic review of the latest applications of automation technologies for construction site safety management, as well as highlight areas less examined for future research to address.

METHODOLOGY: This paper followed a three-step process to select the relevant literature. The results are presented in two parts: a bibliometric analysis that identifies the research trends, and a content analysis of the safety applications within different sectors, namely construction robotics, virtual reality, building information modelling tools, and artificial intelligence.

FINDINGS: According to the bibliometric analysis, the construction phase and hazard identification were the most researched topics. In addition, the content analysis discussed the key safety applications that were implemented within each branch of technology.

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ORIGINALITY: This review presents the state-of-the-art applications of automation technologies in construction site safety management, identifies the existing gaps, and recommends future research topics.

KEYWORDS: *Systematic Review; Safety Management; Construction Site Safety; Automation; Robotics; Virtual Reality; Building Information Modelling; Artificial Intelligence*

INTRODUCTION

Construction is an essential industry that contributes significantly to economic and infrastructural development. Nevertheless, the health and safety concerns of the labour worker as an individual remain a prevalent issue globally. Looking at construction sites in particular, the US Occupational Safety and Health Association (OSHA) listed the top four hazards as falling from height, electrocution, struck by object, and caught in-between (Arias, 2008). In addition to concerns for physical health, undesirable work that is considered repetitive, unhygienic, or dangerous in nature can also negatively impact workers' mental and psychological wellbeing (Tafazzoli, 2022). In response, technological advancements in automation have opened new doors to better efficiency and quality. Although there were past efforts to review the potential of several automation technologies in the Architecture, Engineering and Construction (AEC) industries, few of them reviewed technologies for safety management specifically due to the novelty of automation technology and the industry's resistance to change. Therefore, there is a pressing need to elevate the conversation on safety for construction projects. To fulfil this need, this paper aims to identify the latest trends and gaps in automation research in relation to construction site safety management. This aim is achieved through the following objectives:

1. identify the automation technologies that impact construction site safety;
2. study the existing implementation studies of each technology for site safety management;
3. discuss the research trends and gaps of the existing literature;
4. present recommendations and future research ideas based on the current trends and gaps.

METHODOLOGY

This systematic review followed a three-step literature selection process (see Figure 1), followed by a bibliometric analysis and content analysis of the selected literature. The literature search was conducted on the Scopus database. First, the starting keywords used were "safety" AND "automation" AND "construction"; this yielded 1,332 results. Then, some general filters were used to limit the search to: (1) articles, conference papers, and book chapters only; (2) published between 2013 and 2023; and (3) English only results. These filters reduced the total count to 695 results; these were then used to generate bibliometric networks using VOSviewer. The next step involved further filtering the results by technology, and the resulting list of studies was screened for relevance based on title, keywords, and abstract. As a result, 66 publications remained for further reading. The publications that were reviewed in-depth and discussed are hereafter called the relevant literature. The following section presents the bibliometric analysis of the relevant literature and discusses the implications of these results. The branches of technology discussed in this review are construction robots, virtual reality (VR), building information modelling (BIM) tools, and artificial intelligence (AI).

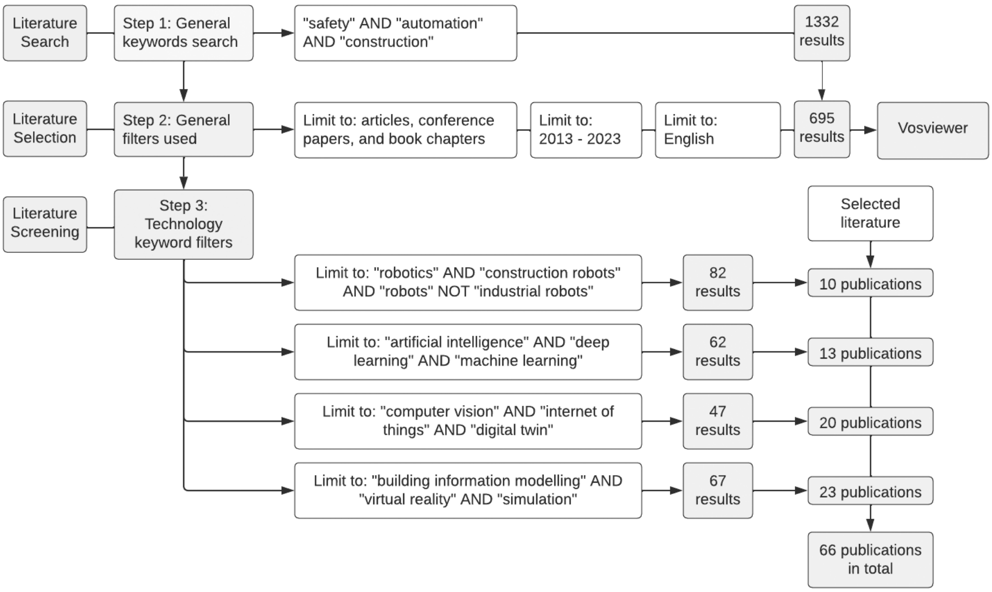

Figure 1: Literature Search, Selection and Screening Process
Source: Constructed by authors

BIBLIOMETRIC ANALYSIS

First, Figure 2 shows that the relevant literature in automation for construction safety significantly and suddenly increased after 2019. Next, Figure 3 describes the relative distribution of technologies in the relevant literature. The branch of technology with the highest publication count was AI and its sub-topics (i.e., Internet of Things, computer vision, deep learning, machine learning), amounting to 35% of the relevant literature. Then, BIM-based tools and robotics made up 21% and 15% of the relevant literature, respectively. Lastly, VR was the lowest count at 14%, indicating a limited exploration of VR in safety management.

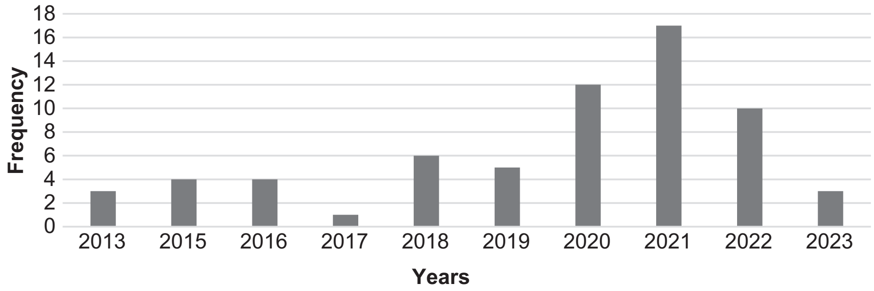

Figure 2: Distribution of Relevant Literature by Year
Source: Constructed by authors, based on Scopus search

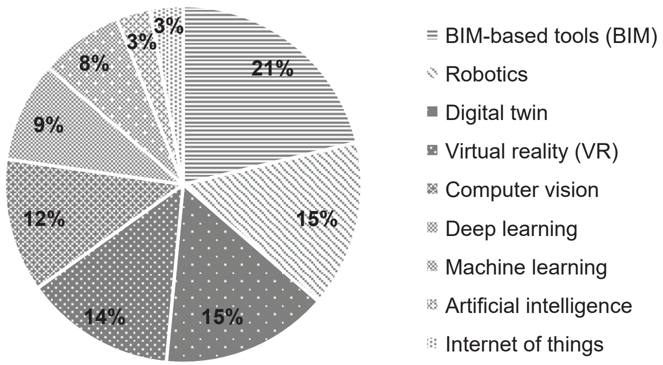

Figure 3: Distribution of the Relevant Literature by Technology
Source: Constructed by authors, based on Scopus search

CONTENT ANALYSIS

Trends in Robotics

Technological Applications

Research on technological applications spanned different sectors of the construction industry towards the same goals: increase productivity and reduce sources of accidents and fatalities. The earliest application found in the relevant literature was the use of Robotic Beam Assembly (RBA) in building projects. Jung *et al*. (2013) described RBA as an automated system for steel beam assembly. Teleoperation enables the user to control the robot remotely. This application eliminates the risk of operator injury onsite, as they would instead use visual information and joysticks to control the RBA system remotely. This technology was only verified by application in a simulated work environment, rather than in an actual construction project.

In modular construction, robotics can automate repetitive activities with higher accuracy, efficiency, and safety. For example, Johns *et al*. (2020) discussed the use of hanging robots for the installation of curtain wall modules in building units. Traditionally, these modules are raised to the connection position during installation by a crane, hoist, or telescopic handler, then fastened with supports attached to the structure. However, this created a collision risk that could lead to personal harm or damage to the modules. Therefore, the authors' proposed solution of the hanging robot mitigates this risk. However, this paper simply explores areas of improvement on current conventional methods and makes various assumptions in doing so.

Lastly, in the tunnel construction sector, the biggest threat to workers is tunnel collapse or (something related to) heavy machinery. As such, new robot inventions emerged in recent studies to fulfil the role of the operator's dangerous task. For example, Li *et al*. (2019) designed a mobile robot model for the purpose of completing construction drilling tasks more safely. Similarly, Yang *et al*. (2021) proposed a robot invention whose task is to replace old components in tunnel boring machines. This invention eliminates operators' exposure to risks associated with underground drilling operations, such as tunnel collapse. Although the possibilities are wide for adopting construction robots, the research found in this field showed a noticeable lack of real case studies. This was expected because of the varying levels of acceptance towards using robots in construction industries across the world and due to the limited attention to safety management. Therefore, future research should look to collaborate with industry stakeholders and government entities who can benefit from these innovations.

Safety Assessment

Construction sites are dynamic environments; this makes routine safety inspection a time-consuming process. Therefore, some studies focused on presenting automated methods to carry out safety inspections. For example, McMahon *et al*. (2018) presented two methods for deploying a trip hazard detector. First, as a support tool used by safety inspectors during routine site checks, second, as an automated system installed on a drone that routinely scans the area for dangers (Kim *et al*., 2018). Also, Habbal *et al*. (2019) proposed using cameras attached to hard hats with object detection and identification capabilities. This approach helps legalise the use of smart safety hats to monitor site activity and report anomalies in real-time; this can be accessed by site managers and for government-enforced safety inspections (Habbal *et al*., 2019). Furthermore, this technology can encourage workers' safety compliance on site.

In another study, Li *et al*. (2019) described the use of patrol robots; these are autonomous machines that can identify defects or other issues in place of a human inspector, with higher accuracy and efficiency. Finally, Johansen *et al*. (2021) developed drones that scan construction sites for safety equipment and emit alerts for their absence or identified flaws. In addition, these drones can provide location information on safety objects in a 3D map layout for operators to find them swiftly during emergencies (Johansen *et al*., 2021). The majority of papers provided recommendations centred on the technology's performance: a clear indication of the early-stage development at which robotics in construction safety stands. Undoubtingly, there is room for improvement before non-technical aspects can be researched and understood. It is important that these proposed applications are further researched so that confidence is also asserted in real life applications.

Trends in VR

Virtual reality (VR) is a digital, three-dimensional, interactive environment that can simulate real-world scenarios; this proved effective for safety training due to its multisensory, immersive experience (Zhang *et al*., 2020). However, there were no studies discussing the comparison between VR training and traditional training methods, which were reviewed in this paper.

As previous reviews highlighted, safety training is the primary domain that takes advantage of utilising VR technology. As new technology is gradually adopted and integrated into construction sites, it is important to upskill or reskill workers in tandem. This is because not all manual labour can be fully automated at once, and the need for skilled workers will rise during this transition (Autor, 2015). For example, Kayhani *et al*. (2018) developed a VR application called *VrCrane* that simulated operating a heavy-lift mobile crane for modular construction. According to the authors, the purpose of *VrCrane* was to train workers in a risk-free virtual environment, as this task is costly, potentially dangerous, and requires precise planning. The authors tested the application using a real model of a construction site for a modular petrochemical plant.

Similarly, Adami *et al*. (2021) responded to this need by developing a VR-based training program on robotic teleoperation for construction workers. In their study, the authors compared the effectiveness of the VR-based program with the traditional training programme for robotics safety and skill training. The results of the study revealed that workers who were VR-trained showed significant improvement over those that were traditionally trained in their knowledge, operational skills, and safety behaviour in relation to robotics. On the other hand, workers' unfamiliarity with, or resistance to, new technology can also cause major safety concerns. Adami *et al*. (2022) continued their investigation on VR-based training, focusing on human-robot interaction behaviours. In this follow-up study, the authors compared the VR-based training program to a traditional programme. The workers that trained with VR reported higher trust in robots, improved self-efficacy, and greater situational awareness. The results of these studies suggest that VR-based training is a promising, and perhaps necessary, step to improve construction site safety practices.

Trends in BIM

Design-for-Safety

Hamil (2021) defined Building Information Modelling (BIM) as a methodology concerned with managing information during the project life cycle. BIM software is a program that facilitates the integration and exchange of data from different sources. The first major domain in BIM-based safety management was the integration of an automated safety checking system with modelling software. These BIM-based tools were developed to facilitate the design-for-safety approach before construction began, using a hazard identification system. In general, the way this system worked was by designing an algorithm that takes in information on safety (e.g., list of safety regulations) and scans 3D building models for non-compliance with these parameters (Hongling *et al*., 2016). In Hongling *et al*.'s (2016) study, the researchers introduced a method to convert safety codes and regulations into machine-readable format, which allowed for better interoperation with other software. Based on this approach, other automated safety-checking systems were developed for specific site accidents, such as fall hazards (Rodrigues *et al*., 2021), for struck-by accidents (Heidary *et al*., 2021), and for structure-related activities (Mihić *et al*., 2018). In the case of Heidary *et al*. (2021), their tool was demonstrated in a residential building project in Tehran, Iran, where it was met with a positive response by the project team for its higher accuracy and faster detection compared to traditional methods.

Other studies aimed to develop holistic systems that detect multiple sources of accidents. For example, Malekitabar *et al*. (2016) argued that a reliable automated safety-checking system was not complete without considering safety risk drivers. Therefore, the authors presented a detailed set of risk drivers detectable from the design phase for the four most common types of site accidents. Furthermore, Lee *et al*. (2020) developed and implemented a design-for-safety review tool to assess the risk of falling, tripping, collision, getting hit by object, and getting stuck in-between. However, the authors suggested more research is needed to account for different safety standards in other countries, as their tool was built to meet safety standards in South Korea, specifically. These systems were also used as part of the design-for-safety approach. The earliest example of this application was Zhang *et al*.'s (2013) system; this detected hazardous areas and suggested specific safety measures in response. In their study, the researchers validated the usability of their system by evaluating the model of a real building project. Similarly, Rodrigues *et al*. (2021) developed a safety plugin that automatically detected and applied safety objects for fall hazards during the design phase in Autodesk Revit building models. Overall, these studies showcased the extensive capabilities of BIM-based tools to detect and respond to construction site safety concerns using different sources of data.

Site Planning

The safety-checking systems described above detected hazards associated with design and worker behaviour. The next research domain in BIM-based tools for safety focused on prevention-through-design in planning construction sites and heavy equipment operation. For example, Pan *et al*. (2017) presented an automated approach to determine optimal feasible locations for mobile cranes during site planning using simulations. First, the BIM model and schedule plan were integrated in a simulation system. Next, the system considered environmental, operating, and safety constraints of mobile cranes as well as collision detection. Lastly, the system generated a 3D visualisation of optimal locations for the mobile crane.

Building on the previous concept, Tak *et al*. (2021) proposed a framework for managing simultaneous mobile crane operations in a simulated environment using BIM data. The authors explained that the simulation can detect onsite collisions based on location data, and they implemented their system on real construction projects in Alberta, Canada. Their case studies demonstrated the system's potential for micro- and macro-scale site planning and constructability analyses. Likewise, Hu *et al*. (2021) developed a hazard identification framework for tower crane operations. With this framework, hazards can be anticipated and mitigated during the planning phase. This area of research is fairly recent and underdeveloped; therefore, it has great potential to grow in parallel with the advancement of modular and robot-assisted construction and requires further studies emphasising real-case use.

Safety Monitoring

Researchers concerned with real-time safety monitoring developed BIM-based safety-checking systems for the construction phase. For example, Liu *et al*. (2020) proposed an automated safety-warning system to proactively monitor site safety during construction. The authors' proposed system classified worksite zones as dangerous, high-risk, or low risk, after which it tracked workers' real-time positions around the site. The workers received warning messages if they were in a dangerous or high-risk zone without their fall protection harness connected to a safety anchor. The authors presented case scenarios based on a real residential building to demonstrate how the system works. Finally, they mentioned that future developments in hazard-zone identification should consider linking the BIM model to the project schedule, as that will mitigate the need to update the system regularly throughout the construction phase.

In addition to building projects, Collado-Mariscal *et al*. (2022) proposed a similar risk assessment tool for linear works projects, and more specifically road projects, which received less attention in the literature than building projects. Similarly, Li *et al*. (2022) created and implemented a safety-checking system for real-time monitoring during construction for a subway project. In their study, the authors considered both safety regulations and safety risk factors using a semantic approach to integrate heterogeneous data. Then, they surveyed experts in the field, who agreed that the system was useful and more time-efficient than manual safety checking. For future research work in this domain, industry collaboration would be a major step forward in verifying the use of these systems over long project durations.

Trends in Artificial Intelligence

According to Rai *et al*. (2019), AI describes the ability of machines to perform cognitive functions that are associated with human minds, such as perceiving, reasoning, learning, and interacting with the surrounding environment. Such smart systems rely heavily on machine learning to allow for intelligent capabilities (Kee Wong, 2021). According to Janiesch *et al*. (2021), machine learning is the capacity of systems to learn from problem-based training to automate the process of analytical model-making. Moreover, deep learning is a subset of machine learning based in using artificial neuron networks (ANNs) (Janiesch *et al*., 2021). Grossi and Buscerna (2007) defined ANNs as artificial adaptive systems that are inspired by the functioning processes of the human brain. Only recently did AI technology find its way to construction research sometime in the past decade (Teicholz, 2013).

Machine Learning

Construction accident classification is the primary application around which machine learning is implemented. In recent years, researchers have proposed a binary model to classify the severity of accidents. The earliest model was developed by Esmaeili *et al*. (2015) (which they called logistic regression), to predict the severity of accidents, being categorised as either 'fatal' or 'non-fatal'. Similarly, a more recent study on construction accident classification was conducted by Ayhan and Tokdemir (2020), who classified accidents into two categories titled 'low-severity' and 'high-severity'. Similarly, Koc and Gurgun's (2022) severity model allowed for the prediction of future events using a number of factors that affect the likelihood of dangers occurring on site. For example, the researchers' statistical analysis showed that the likelihood of fatality increases proportionally with the age of workers, ranging from 0.93% for ages below 20 to 4.06% for ages above 50. However, this field of research lacks implementation studies with real cases. Moreover, the benefits of these models for industry use are not widely known or made clear; this lowers the chance of construction stakeholders investing in them.

Deep Learning

According to the United States Occupational Safety and Health Association (OSHA), the primary causes of construction fatalities are fall hazards, object striking, electrocution and being caught in-between objects (Arias, 2008). A majority of these fatalities are preventable with proper use of Personal Protective Equipment (PPE), such as hard hats, safety vests, and safety goggles (Nath *et al*., 2020). However, it is generally challenging to ensure all workers adhere to safety regulations, and non-adherence can result in accidents or fatalities. Therefore, the first area of research involving safety applications supported by deep learning was the real-time detection of PPE during work hours. To date, several deep learning algorithms have been developed in hopes of achieving this objective (Lin *et al*., 2017). Most recently, You Only Look Once (YOLO) was found to be the fastest and most accurate algorithm (Redmon *et al*., 2016). To establish the accuracy of the algorithm, Xiaolu *et al*. (2021) developed a detection system that can identify hardhats, body clothing and gloves. In detection technology, the mean average precision is the metric used to evaluate the reliability of detection systems. Tests were conducted by Xiaolu *et al*. (2021) to determine the AP detection of different PPE, giving a very high value that translates to high accuracy. In practice, Zhang *et al*. (2022) developed a drone-based YOLO detection system in the construction of Transmission Lines. However, the technology is yet to be tested in a case study format where more constraints must be taken into consideration.

The second area of research around deep learning was focused on the detection of abnormal construction activity. For example, Lin *et al*. (2021) proposed an image-based analytics model to identify irregular construction activity through a crew bar chart. This model produced by

Lin *et al*. (2021) allows the party in charge to evaluate these timings and check for possible safety interruptions based on the movements of workers and construction vehicles. Although the authors achieved the set research objective, the proposed framework has limitations for real life applications. The authors' model was tested under a controlled environment that does not fully reflect the dynamic nature of real construction sites. Yang *et al*. (2022) argued that as technology progresses, more applications in construction will become economically and technically feasible.

CONCLUSIONS AND FUTURE RESEARCH

To conclude, there have been many new research developments towards a safer and more productive work environment for construction projects. While some automation technologies are still in early development, others are gradually gaining traction in the AEC industry of developed countries. For instance, the use of robotics and AI during the construction phase can reduce the exposure of labour to unsafe working conditions and to increase productivity. Next, VR training shows promise for both skill and safety training for workers. On the other hand, BIM-based tools received considerable attention in the last decade for many purposes within the planning and design phases. Table 1 presents future research recommendations for each research field.

Table 1: Summary of Research Gaps Identified

Technology	Safety Applications	Main Research Gaps Identified
Robotics	Technological Applications	• Conduct implementation case studies • Conduct cost-benefit analysis studies
	Safety Assessment	• Develop acceptance criteria to legalise the use of robotics
VR	Safety Training	• Expand training to more construction activities • Investigate the impact of workers' technological aptitude on effective VR-based training • Develop frameworks for VR-based training programs and applications • Compare the effectiveness of VR-based training and traditional training programmes
BIM-based tools	Design-for-Safety	• Develop criteria for design-for-safety and prevention-through-design in automated safety checking systems • Review design-for-safety requirements used in various BIM-based tools
	Safety Planning	• Establish criteria for safe site planning, considering locations of heavy equipment
	Safety Monitoring	• Define the role of site managers and workers in relation to safety liability • Combine BIM and AI to create more sophisticated tools for monitoring workplace safety

(continued)

Table 1: Summary of Research Gaps Identified *(continued)*

Technology	Safety Applications	Main Research Gaps Identified
AI	Machine Learning	• Evaluate accident severity models in long term projects for performance • Develop accident prediction models
	Deep Learning	• Conduct implementation case studies • Expand the detection capabilities of deep learning algorithms

Source: Constructed by authors

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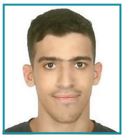
Yara Elenany received her BSc in Civil Engineering from the American University of Sharjah, UAE. She then joined the Construction Management Master's programme in the same university, working part-time as a graduate teaching assistant. During her Master's study, she co-authored two papers that were presented in international conferences.



Seifeldin Abbas has a BSc in Civil Engineering from the American University of Sharjah, UAE. Seifeldin has a lifelong interest in civil engineering and problem solving, and has now enrolled for an MSc in Construction Management.

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