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Systematic Review

BIM for Safety: Applying Real-Time Monitoring Technologies to Prevent Falls from Height in Construction

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Abstract: There are significant risks in the construction sector, with falls from height identified a greater hazard than in most other industries. Efforts to improve working conditions and reduce accident rates have driven research into real-time monitoring technologies to reduce the risk of falls. The main objective of this research is to review existing real-time monitoring technologies, identify the most relevant, and analyse their benefits and impact on reducing workplace accidents in the construction sector. A systematic review was conducted using PRISMA methodology to investigate the use of real-time monitoring technologies in the construction industry. Only studies specifically investigating real-time fall risk assessment were included. Of the initial 446 articles reviewed, 39 were considered highly relevant to the research objectives. Various wireless and computer vision technologies were identified for real-time worker monitoring, often integrated with BIM to improve workplace safety. The findings suggest that a combination of technologies may produce more effective results for worker monitoring. However, further research is needed to verify the applicability of these technologies on construction sites.

Keywords: monitoring; technology; BIM; fall from height; safety

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1. Introduction

Based on data from the European Union global accident report, the construction industry is considered high-risk, with construction sites being the most dangerous environments compared to those of other sectors [1]. The main causes of accidents include falls from height, being struck by objects, rollovers, and falling objects [2]. The Occupational Safety and Health Administration (OSHA) reported that the lack of fall protection was the most common safety violation in 2023 [3].

As falls from height are the leading cause of fatal and non-fatal accidents in the construction industry, several protective measures have been developed and implemented. These include guardrails, safety nets, personal protective equipment (PPE), as well as preventive measures such as worker safety training [4] and prevention through design [5]. Despite these precautions, the number of accidents at work due to falls from height continues to rise [6], as shown in Figure 1.

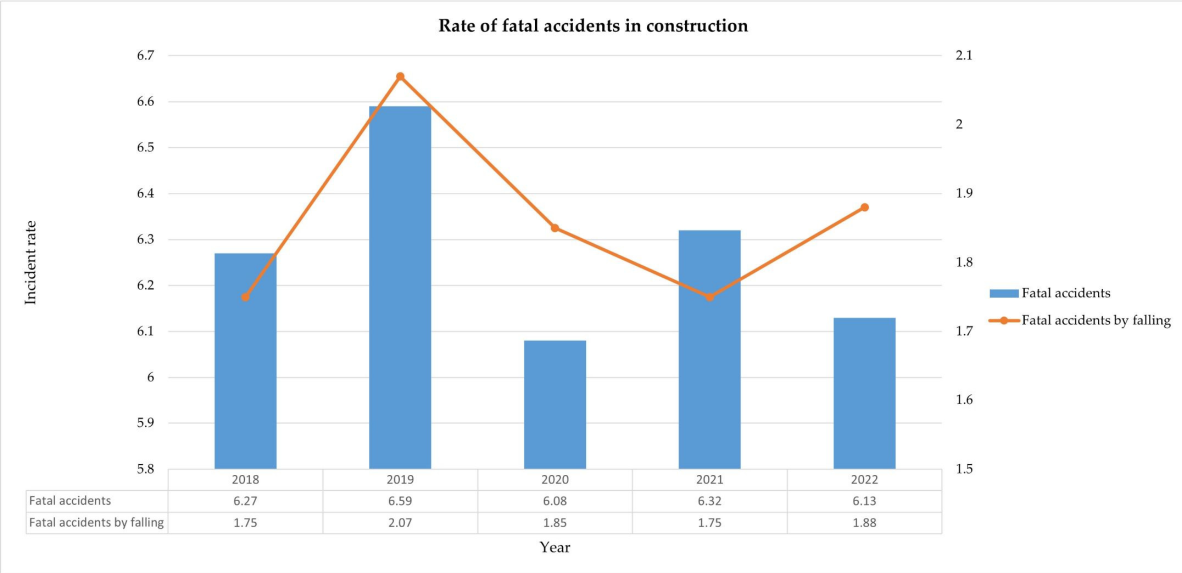

Figure 1. Number of fatal accidents in UE [6].

Most construction accidents are caused by unsafe behaviour, and reducing or eliminating such behaviour is likely to improve workplace safety [7]. Traditional methods of determining worker behaviour are predominantly based on observational methods. While these methods can provide valuable insights, they are time-consuming, labour-intensive, and subjective. As a result of these limitations, existing studies have employed computer vision to identify unsafe actions by workers in the field [7], namely the incorrect use of personal protective equipment; wearable sensors to assess hazardous behaviour by workers while performing work [8]; and location technologies that can identify whether a worker is in a hazardous situation [9], thus preventing accidents at work.

The traditional approach to monitoring workers relies on observations made by safety engineers, which are both time-consuming and inefficient for large, complex sites.

Changes to original plans during construction often create new hazards, and the ever-changing environment of construction sites makes it difficult to apply safety measures promptly [9]. In addition, high accident rates in the sector indicate that current methods are insufficient to reduce workplace accidents [10].

The construction industry displays characteristics that set it apart from other sectors, i.e., it is complex, with many hazardous processes and working environments in day-to-day operations; there are many overlapping activities, equipment, and trades; and frequent changes occur throughout the construction process [11]. As a result, research has focused on continuously monitoring ongoing work to enhance the effectiveness of safety strategies, with automated management technologies acting as supplementary safety tools [12].

Construction sites need to evolve into intelligent workplaces where the real-time monitoring of worker behaviour is required to respond to and prevent accidents and injuries [13].

Tracking technologies, when integrated with various software modules that implement risk identification and alerting algorithms, are fundamental to proactive safety systems on construction sites, enabling real-time monitoring of the location of workers and assets [9].

Building information modelling (BIM) is a methodology that uses digital models to manage all phases of a construction project, from design to maintenance, integrating information on materials, costs, and schedules. It improves efficiency, reduces errors, and contributes to faster and safer deliveries. In terms of safety, BIM makes it possible to identify and simulate risks before physical execution, helping to plan accident prevention measures.

Detailed visualisation and coordination between teams reduces miscommunication and promotes a safer working environment [14].

Several studies have highlighted the relevance of BIM in construction safety management, looking at its various applications, such as knowledge-based solutions based on the prevention through design (PtD) approach [15], automated compliance checks that allow for the identification of high-risk areas during the design phase [16], and the verification of compliance with local regulations [17]. In addition, BIM facilitates the detection of site conflicts by identifying the proximity between workers and equipment [18], provides proactive feedback using temporal and spatial data to assess worker safety [19,20], supports worker training [21], and enables the analysis of worker behaviour by detecting inappropriate use of personal protective equipment (PPE) [22] or integration with behaviour based safety (BBS) [23], helping to raise worker awareness and correct unsafe practices.

Regarding the integrated use of BIM with real-time monitoring technologies, the study by Fargnoli et al. [24] shows promising research that provides real-time alerts for unsafe worker behaviour. This research challenge covers not only the individual level, but also focuses on the interactions between workers and the site environment. Another approach is to use BIM in the lifecycle maintenance of the building, where BIM can bring benefits in terms of reduced equipment downtime, reduced costs, and increased customer satisfaction, while improving the exchange of information between stakeholders [25]. Recent evidence suggests that more practical applications of BIM are needed, particularly in regards to safety training and education, using the technology to strengthen the climate of safety and resilience and promoting the development of quantitative risk analysis to support safety management more effectively [24].

The main objective of this article is to analyse the existing technologies in this field of research in order to identify the different types of real-time monitoring technologies related to falls from height, their integration with the BIM methodology, and their contribution to the improvement of occupational safety and health in the construction sector. In light of the above, this article consists of a systematic review carried out using the PRISMA (preferred reporting items for systematic reviews and meta-analyses) review protocol [26,27] to assess the current state of the field and provide recommendations to guide future research into real-time worker monitoring technologies in the construction industry.

This paper is structured as follows: Section 2 outlines the methodology for reviewing the existing literature, Section 3 presents the findings, Section 4 discusses these findings, and the paper closes with concluding thoughts and recommendations for future research.

2. Materials and Methods

This section outlines the systematic review process, which followed the PRISMA methodology [26,27] to analyse all relevant literature related to the research question in a clear and precise way [28]. This helps to make the process more transparent, standardised, and reliable, so that other researchers can easily understand and reproduce the results. Using PRISMA improves the quality of research, makes it easier to find relevant studies, and increases the credibility of the results. In short, PRISMA ensures that the review is well done and reliable [28].

Information was searched in relevant international engineering databases and journals in different scientific fields, i.e., Scopus and Web of Science [29]. These databases were consulted between 10 November 2024 and 17 November 2024. The search strategy included a combination of the following keywords: “construction”, “building”, “risk assessment”, “risk management”, “safety”, “real-time”, “BIM”, “building information model”, and “fall”.

Keywords were combined as follows (construction OR building) AND ({risk assessment} OR {risk management} OR safety) AND (“real-time” OR BIM OR “building information model") AND (fall*). Title, abstract, and keywords were applied to Scopus, and topic was selected from Web of Science. In each of the databases, filters were applied to limit the selected documents by type of document (research articles), type of source (indexed peer-reviewed journals), and language (English). The query and filters adapted for each database are shown in Table 1.

Table 1. Search phrases by database.

Databases	Query and Applied Filters
Scopus	(TITLE-ABS-KEY (construction OR building) AND TITLE-ABS-KEY ({risk assessment} OR {risk management} OR safety) AND TITLE-ABS-KEY ("real-time" OR bim OR "building information model") AND TITLE-ABS-KEY (fall*)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English"))
Web of Science	construction OR building (Topic) AND {risk assessment} OR {risk management} OR safety (Topic) AND "real-time" OR bim OR "building information model" (Topic) AND fall* (Topic) and Article (Document Types) and English (Languages)

The search was extended by analysing the reference lists of the initially selected articles and by snowballing until no further relevant articles were found.

Studies were only eligible if they were (1) used in the construction sector, (2) assessed the risk of falls from height, and (3) monitored the risk in real time. When the articles were read in full, relevant information from each study was collected and summarised in a table, including the authors' names, year of publication, country, equipment and software used, application in a real construction context, study results, and main conclusions.

This article used a mapping and visualisation tool, VOSviewer, which allows data to be presented in an optimised visual form [30]. Therefore, the scientific articles included in this review were examined using VOSviewer software (version 1.6.20) to analyse collaboration patterns between countries and perform a citation analysis to identify key trends in the literature and significant sources [31].

3. Results

3.1. Bibliometric Analysis

3.1.1. Study Selection

Following the PRISMA guidelines [26,27], the process of identifying relevant articles for this review began with an initial collection of 449 studies, as shown in Figure 2. After filtering and removing duplicates, 44 articles remained for eligibility assessment. Of these, 30 were excluded for reasons such as not focusing on real-time risk assessment, not addressing falls risk, or being literature reviews, leaving the remaining 14 articles eligible for inclusion. Snowballing was then used to identify an additional 25 relevant studies, bringing the total number of articles analysed in this review to 39.

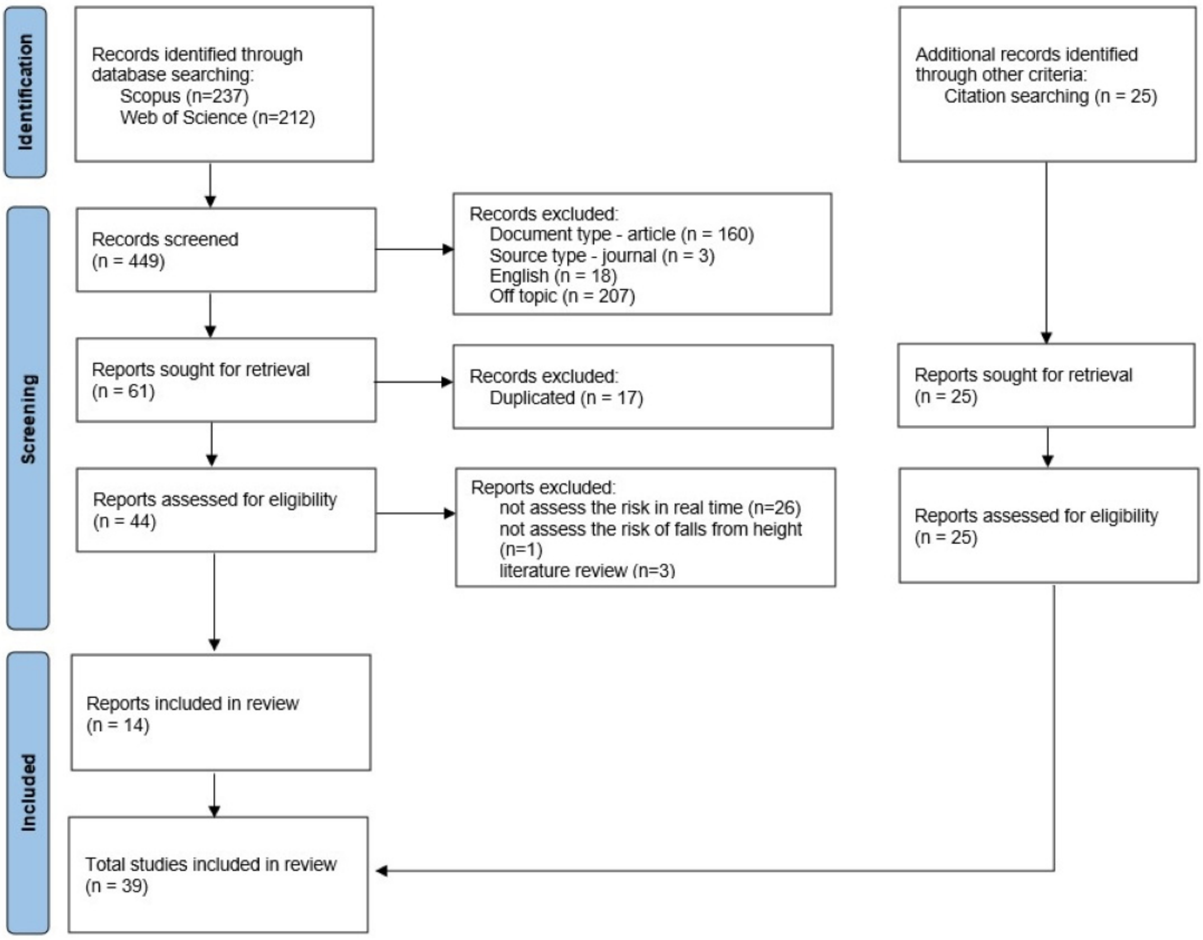

Figure 2. The process of selecting studies using the PRISMA methodology.

3.1.2. Publishing Framework

After reviewing the literature and following the analysis protocol described above, the results were categorised to define the editorial framework of the texts examined. Figure 3 shows the yearly distribution of the articles selected for the study regarding real-time monitoring technologies and building safety. At first glance, there is a clear upward trend in the number of articles on this topic, even taking into account that the data for 2024 and 2025 are incomplete at the time of this writing.

Scientific collaborative networks can help identify the leading research groups in a particular field, providing researchers with insights into the research frontiers [32]. Figure 4 illustrates the collaborative network of 15 countries based on research contributions identified through co-authorship analysis in this study, with larger node sizes for China, South Korea, and Australia, indicating their more significant contributions to real-time security monitoring research.

Figure 5 shows the 23 journals publishing research on real-time fall monitoring, with Automation in Construction and the Journal of Construction Engineering and Management emerging as the leading journals, as shown by the node sizes and connection strength in the network analysis.

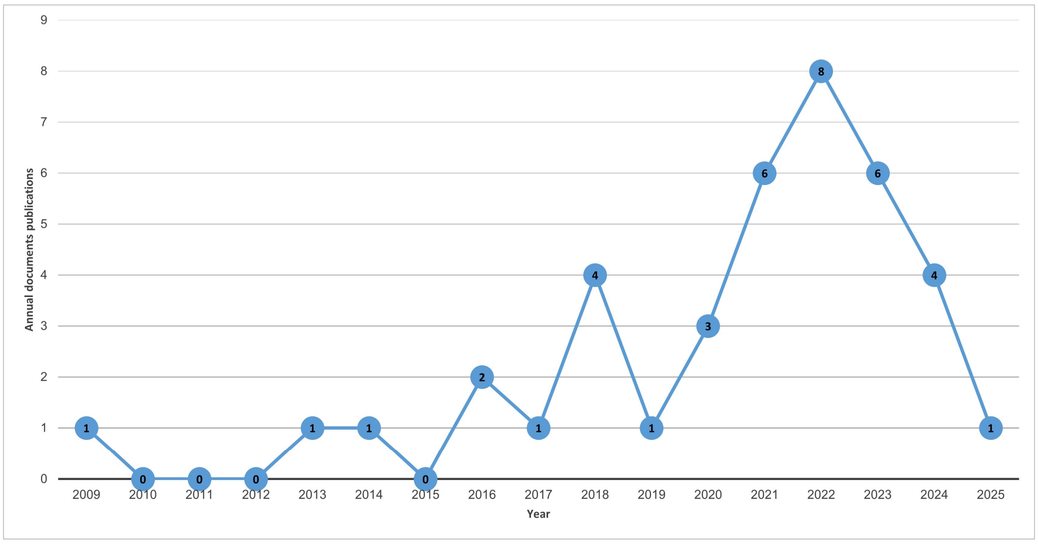

Figure 3. Annual distribution of articles.

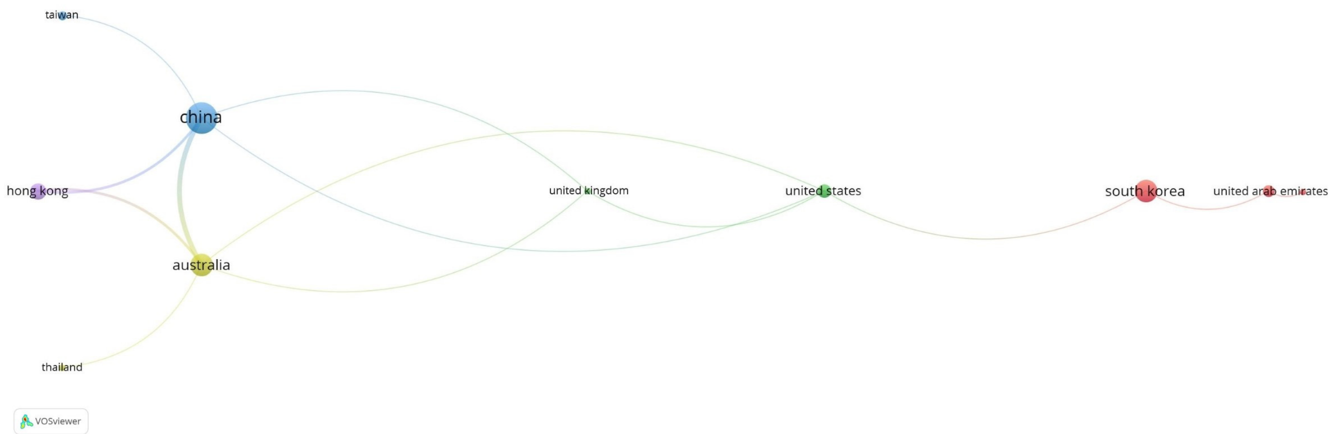

Figure 4. Networking and global reach of countries participating in real-time safety monitoring.

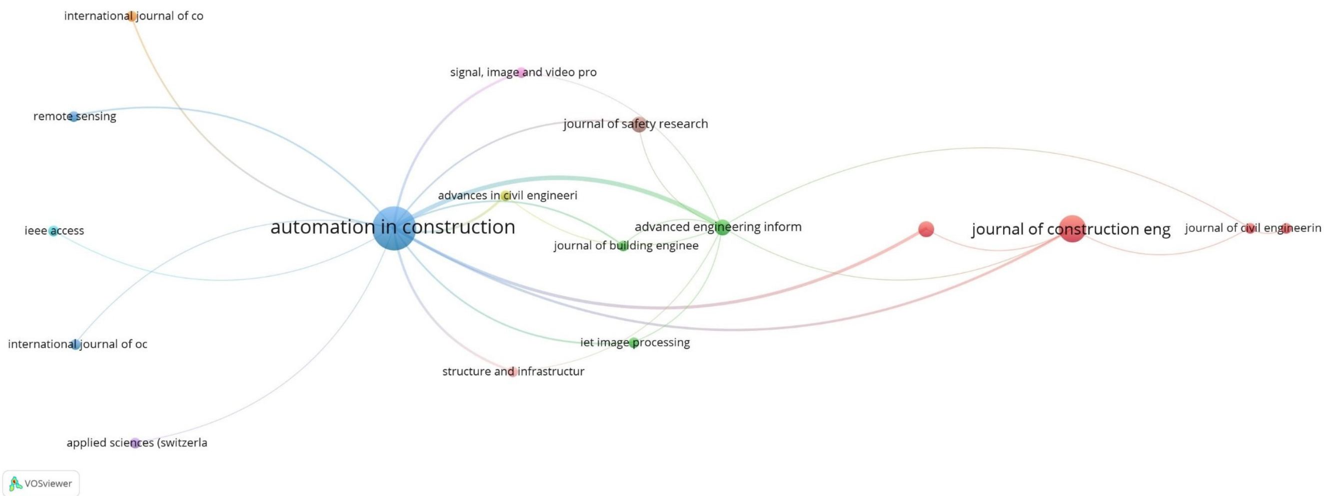

Figure 5. Network of citation sources for the journals publishing the included articles.

The main content of the published documents and the types of areas studied in a particular domain are indicated by keywords, and the proximity between keywords is indicated by their co-occurrence [33]. Following the suggestions of Hosseini et al. [34], in this study, "author keywords" and "fractional counting" were used in the VOSViewer analysis. The minimum number of keyword occurrences was set to 2. Out of a total of 142 keywords, 22 met the threshold. Some other keywords with the same semantic meaning, such as 'falls' and 'fall', were combined, and finally, 17 keywords were selected, as shown in Figure 6.

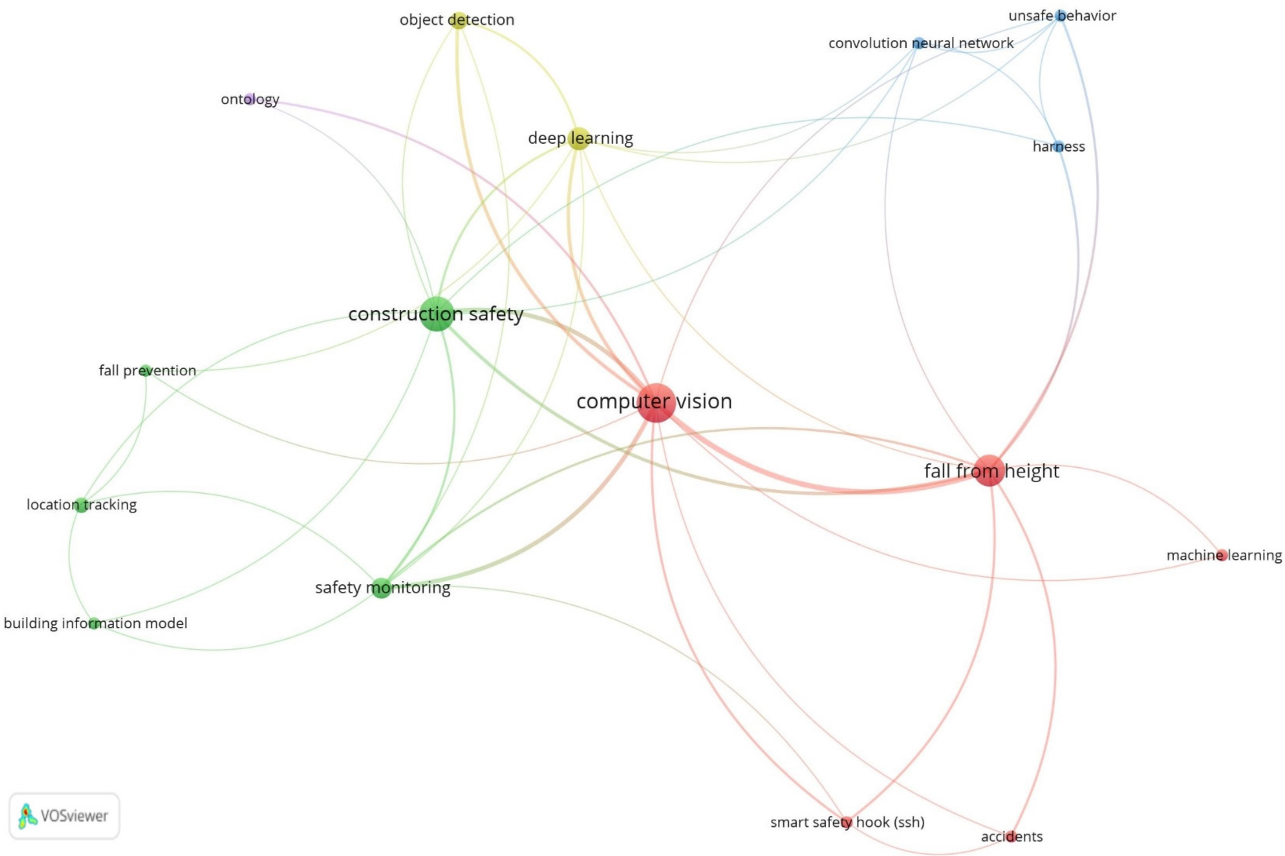

Figure 6. Keywords co-occurrence in fall from height research.

3.2. Scoping Review

3.2.1. Real-Time Monitoring of Workers

The main challenge in construction safety is preventing accidents, with safety performance focusing on maintaining safe workplaces. This can be achieved through the safety culture of an organisation, the safety behaviour of workers, or by minimising accidents and occupational injuries on site [35]. Safety performance can be improved through both proactive and reactive approaches. Reactive technologies collect data in real-time, but require subsequent processing to extract meaningful information. Proactive technologies, on the other hand, operate in real time and provide immediate warnings and alerts to workers about hazards as they occur [36].

Several studies have examined proactive accident prevention techniques based on real-time workplace and worker monitoring technologies to improve workplace safety [12]. These technologies include the use of wearable sensors, surveillance cameras with video analytics, GPS tracking devices, and artificial intelligence-based warning systems. These tools make it possible to identify risky behaviour, hazardous environmental conditions, and potential security breaches before serious incidents occur [12].

In addition, integrating these technologies with ongoing training programmes and promoting a robust safety culture helps to reduce accidents. The active involvement of management and workers in identifying and mitigating risks is fundamental to the success of these approaches. In this way, the combination of proactive technologies and effective safety management practices creates a safer, more resilient working environment, adapted to the dynamic demands of the construction industry [36].

3.2.2. Monitoring by Radio

Positioning technologies commonly used in research include the Global Positioning System (GPS), wireless local area networks (WLANs), radio frequency identification (RFID), Bluetooth Low Energy (BLE), and ultra-wideband (UWB) systems. These technologies are often used to track objects in the field, such as construction workers [9] and mobile equipment [36]. Their use is critical to the advancement of safety management automation in construction.

Radio localisation is used to identify hazards by assessing the proximity of workers to hazardous areas. In some cases, RFID technology is used to monitor workers and equipment on site in real time by attaching RFID tags to the workers and equipment to be monitored [37]. Each tag contains a communication system that transmits data to a central server and alerts workers if they are in danger.

Numerous studies have used GPS and real-time location systems (RTLS) to track the location of workers on construction sites [38–42]. One study used 3D software to map workers' locations, visualise their positions, and process the data to generate alerts when a worker is at risk [39]. An alternative use of GPS is to map the positions of both workers and equipment in the field, making it possible to identify workers' proximity to hazards, facilitate real-time safety risk assessment, support dynamic evaluation of workers' safety conditions [38,40], and assist safety engineers in decision making.

UWB technology is used to monitor workers and construction sites by equipping workers with wearable tags and installing receivers in designated hazardous areas. This setup, when combined with predictive software, enables the detection of hazardous situations and supports real-time risk management [43].

WLAN technology monitors worker behaviour by integrating a camera into the worker's helmet or goggles, which is connected to a smartphone that transmits the information via a wireless network to the information processing server and issues an alert in the event of a hazardous situation [44].

BLE technology is also being used to monitor workers by installing sensors in safety harnesses [45,46] and in fall-hazard environments [19,47]. These sensors communicate via BLE with a receiver that transmits the data and uses Internet of things (IoT) systems to assess the actual risk and generate alerts for workers in case of non-compliance [45,47].

3.2.3. Monitoring Based on Computer Vision

Computer vision-based surveillance involves monitoring areas of interest using only a sequence of images, making it possible to track multiple targets within a field using a single camera. Advances in computer vision have made this approach a prominent research topic. With the development of modern deep learning (DL) algorithms, such as convolutional neural networks (CNN), region-CNN (RCNN), fast RCNN, and You Only Look Once (YOLO), vision-based tracking has become increasingly accurate and reliable [7,48–71]. Computers can track objects in the field based on their characteristics using models trained with deep learning (DL) algorithms, which effectively capture the complex relationship between input data, such as images, and output reasoning, such as object recognition.

Computer vision has been used in several studies to confirm that workers are properly equipped with personal protective equipment, such as helmets and harnesses [49,51,52,54,56,58,61,62,64,69], and to monitor their actions when using ladders [7,48,55]. This information is then processed using DL algorithms, which can issue an alert if the equipment is not being used correctly, increasing the risk to the worker. Five of these studies have been applied in a real construction context [49,50,53,54,56,58,59,62,65–70], and their effectiveness when applied on a large construction site is unknown.

Some studies have used computer vision to check for the absence of guardrails in an area with a risk of falling and to warn of this situation [60].

It is also possible to use computer vision to track the location of workers and equipment on site, with the collected images used as cross-referenced BIM files to create a virtual construction site, while identifying the hazard and generating an alert in hazardous situations based on DL [53,68,71].

Unmanned aerial systems (UAS) equipped with GPS and cameras have been used to collect images in a work zone, considering construction progress, site conditions, and the surrounding environment. This information is transferred to a digital platform that automatically cross-references the images collected by the UAS and runs a CNN-based DL algorithm to detect workers, vehicles, and equipment, helping to monitor safety conditions on site [72,73].

3.2.4. BIM Software for Fall Risk Prevention

BIM is an approach that focuses on creating and using intelligent digital models during the planning, design, construction, project management, and maintenance phases of buildings and infrastructure, covering the entire lifecycle of the structure. Work processes using BIM tools are developed around a three-dimensional building model in which a substantial part of the relevant information is integrated [14].

Riaz et al. [74] demonstrated the benefits of integrating BIM with sensors for safety by presenting a prototype that monitors confined spaces on construction sites, using BIM to visualise and communicate sensor data such as extreme temperatures and oxygen levels, although the location of workers was not tracked. Some studies have extended this approach to monitoring worker safety, identifying hazards and detecting unsafe incidents in real time by tracking building features in the BIM model, with the data then transmitted via the cloud to relevant safety engineers using BLE technology [19,46] and RTLS or GPS [39,42].

Some authors also use the BIM model to inform workers of the risks they are exposed to. For example, one study [37] developed a safety check system using RFID tracking that alerts workers to potential hazards before they begin their tasks and serves as a reminder of risk factors when performing hazardous tasks. Another study proposed a visual warning system to provide hazard information to workers through wearable magnetic resonance imaging (MRI) goggles, with hazard identification performed on virtual construction sites (VCS) created from BIM models [71].

Some studies have also used the BIM model to cross-check data collected by computer vision [50,53,68], enabling the management of risks faced by workers at any time and generating a safety alert.

3.2.5. Applicability of Different Technologies

Various researchers have used technologies to monitor fall risks in construction, focusing on aspects such as the correct use of PPE, fall risk assessment, workers' exposure to hazards, and their awareness of task-related hazards, as shown in Table 2. However, it is important to note that some of these studies have not been applied to real construction sites.

Several authors have focused on monitoring workers to prevent the risk of falls from height, as this has great potential for practical applications that can assist in monitoring construction sites and potentially improve site safety.

Table 2. Use of different technologies found in the relevant literature.

Technology Used	Type of Monitoring	Use in a Real Work Context	Reference/Literature
Radio-based technology	Identification of construction site risks, not just falls from height.	Yes No Yes Yes Yes Yes Yes Yes Yes	[37] [39] [40] [41] [42] [43] [44] [19] [47]
	Identification of the risks to which workers may be exposed, based on the construction conditions.	No	[38]
	Assessment of the correct use of safety harnesses.	No No	[45] [46]
Vision-based technology	Assessment of the risk of falling from a height when working on a ladder.	No No No No	[7] [48] [55] [57]
	Assessment of the correct use of safety harnesses when workers are on scaffolding.	Yes Yes	[49] [64]
	Identification of construction site risks, not just falls from height.	Yes Yes Yes No Yes Yes Yes Yes Yes Yes	[50] [53] [59] [63] [65] [66] [67] [68] [70] [73]
	Assessment of the correct use of safety harnesses.	No No Yes No Yes Yes	[51] [52] [58] [61] [62] [69]
	Assessment of the correct use of PPE.	Yes Yes	[54] [56]
	Assessment of the absence of guardrails.	No	[60]
	Identification of the risks to which workers may be exposed, based on the construction conditions	No	[71]
	Identification of areas that could lead to unsafe activities, not just falls from height.	Yes	[72]
BIM software	Use of RFID and BIM technology to raise awareness of hazards.	Yes	[37]
	Use of RTLS/GPS and BIM technology to address construction site risks, not just falls from height.	No Yes	[39] [42]
	Use of BLE and BIM technology to address construction site risks, not just falls from height.	No Yes	[46] [19]
	Use of computer vision and BIM technology to address construction site risks, not just falls from height.	Yes Yes Yes	[50] [53] [68]
	Hazard identification using VCS and virtual reality.	No	[71]

4. Discussion

4.1. Comparing Different Technologies

Positioning system technologies are divided into external and internal types. GPS is the most commonly used external system, while internal technologies include Wi-Fi, RFID, laser, infrared, and ultrasound. GPS operates autonomously, without the need for additional technology to provide location services, while RFID enables connections between tagged objects and information systems, providing lightweight communication. However, the low positioning accuracy of RFID can be a challenge when used for rescuing trapped workers in the event of a tunnel accident [75].

Wi-Fi-based real-time location systems (RTLS) are reliable and are managed by dedicated software. Compared to other location technologies such as GPS, smartphone location, RFID, and ZigBee, Wi-Fi offers the following advantages: (1) it works indoors and outdoors, enabling widespread positioning; (2) it uses the existing Wi-Fi network, requiring no modifications, making it cost-effective; (3) its signal is less affected by obstacles, even in non-line-of-sight situations [75].

Research into indoor positioning technologies has resulted in several categories, including conventional radio frequency (RF) technologies, such as Wi-Fi, BLE, Zigbee, RFID, UWB, and indoor GNSS, as well as non-electromagnetic (non-EM) methods, such as ultrasound and geomagnetic waves. Vision-based technologies using full-spectrum light, such as image processing and range imaging, are also part of this development [76].

Despite extensive research, there is no ideal internal positioning system. Each internal positioning technology, principle, and algorithm has its strengths and limitations. As a result, researchers suggest combining different internal and external positioning technologies to address each of their weaknesses and achieve more accurate positioning. This approach, known as hybrid positioning, can be divided into three types: (1) hybridisation of internal and external positioning technologies, (2) hybridisation of internal positioning technologies, and (3) hybridisation of internal positioning principles. In particular, hybrid indoor/outdoor positioning often involves combining GPS with indoor Wi-Fi systems, which is particularly useful in semi-indoor environments, such as construction sites [76].

Li et al. [76] outline the main indoor positioning technologies as follows:

- Wi-Fi: the most widely used wireless communication technology, making it the most common choice for indoor positioning systems.
- BLE: a wireless technology with low power and short-range capabilities that operates in the same 2.4 GHz band as Wi-Fi and is widely available on most smartphones.
- RFID: a well-established short-range communication technology used in various applications such as asset tracking, inventory monitoring, and toll collection. It consists of tags, antennas, and a computer that estimates the target's position.
- UWB: a high-data-rate communication technology that has become popular for indoor positioning due to its accuracy and performance advantages.
- GNSS: external positioning systems such as GPS, GLONASS, GALILEO, and BeiDou are global but cannot be used indoors due to building obstructions. Indoor GNSS systems, often using radio or laser-based signals, solve this problem, allowing smartphones to track positions indoors and outdoors.
- Vision: an emerging technology used to develop vision-based indoor positioning systems with broad applications.

UWB systems provide high accuracy with low power consumption, while RFID and RF-based indoor GNSS systems provide medium to high accuracy. Dedicated indoor GNSS and RFID systems are faster, while smartphone-based GNSS systems are slower. High accuracy indoor GNSS systems are more expensive than RFID systems, while laser-based

GNSS systems offer superior accuracy but are also more expensive. Table 3 compares these technologies [76].

Table 3. Performance comparison of key positioning technologies [76].

Indoor Positioning Technologies	Precision	Power Consumption	Cost	Response Time
Wi-Fi	Low	High	Very low	Long (~1–4 s)
BLE	Low	Low	Low	Very short (~20–30 ms)
RFID	Moderate to high	Low to moderate	Low to moderate	Short (~30 ms)
UWB	High	Low	Moderate to high	Moderate (~300 ms)
Indoor GNSS	Moderate to high	Moderate	Moderate to very high	Short/long (~25–100 ms/~1 s)
Image processing	Low	High	Very low	Long (~2–3 s)

4.2. Hybridisation of Internal Positioning Technology

Recent developments in indoor positioning research offer promising prospects for creating effective on-site systems, with notable trends such as combining different positioning technologies, merging positioning principles, linking with indoor navigation, facilitating infrastructure-free and collaborative positioning, applying game-theoretic strategies, adopting device-free positioning, and incorporating BIM models [76].

The combination of RFID and Wi-Fi is a common method to hybridise indoor positioning technologies and offers a promising solution for IoT and context-aware systems with indoor positioning capabilities [77]. RFID provides higher positioning accuracy, while Wi-Fi is more scalable, so their combination improves the performance of the system. There are two approaches: one involves estimating positions separately with RFID and Wi-Fi systems and then combining them for improved accuracy, known as fusion-based positioning. The other approach integrates RFID tags with a Wi-Fi system, using the tags as accelerometers for position monitoring [76].

A common approach to hybridising indoor positioning technologies is to combine vision with Wi-Fi systems for fusion-based positioning, which can improve accuracy and precision [78].

The studies reviewed did not explore the combination of different technologies to monitor workers in real time, which could provide more accurate data and improve workplace safety.

4.3. Integration with BIM Models

BIM is a digital approach to managing project information throughout its lifecycle. It allows projects to be digitally explored, including their physical and functional aspects, before construction begins. BIM helps deliver projects faster and more cost-effectively, while reducing environmental impact, safety risks, and hazards. It also improves design, visualisation, performance simulation, cost estimation, and documentation accuracy, along with resource planning, management, and monitoring [79].

The construction industry is increasingly adopting BIM, particularly for incorporating safety measures throughout the lifecycle of a building. Technological advances in BIM have also paved the way for proactive safety solutions in the design and management of construction sites [80]. Studies show that BIM can be used effectively for occupational safety planning and accident prevention, improving overall safety management [81].

The management of information using BIM tools allows for a different level of evaluation of the preventive measures to avoid construction accidents and assess the risks present in construction. There are data on the use of BIM to incorporate prevention in the design phase, to simulate construction phases to analyse risks, to draw up contracts with guarantees on prevention levels, to use mobile devices during the execution of work, to use tracking devices to control operations, and to analyse prevention measures during the operation and maintenance phase [82].

BIM has been used to integrate design, risk assessment, and prevention, enabling comprehensive safety management in construction by addressing occupational risks such as falls from height and incorporating them into the building design, demonstrating its applicability to both complex and standard projects at all stages of the construction process [79].

Several BIM technologies, such as BIM design algorithms and rules for automatic safety verification of models, semantic modelling based on safety management knowledge ontologies, and model-based analysis of construction processes to identify hazards, can be used to monitor occupational risks [83]. In addition, 4D BIM is used for occupational risk prevention during the design phase, using BIM-based safety planning and site layout [84]. Virtual reality (VR) is also used for virtual hazard identification and visualisation, as well as for vocational training [21].

BIM is valued for its ability to identify, assess, and manage risk early in the design and construction process [85,86]. The 3D BIM models and 4D design simulations provide a comprehensive view of site conditions and construction phases, enabling project risks to be visualised and allowing designers and contractors to identify hazards, design issues, and safety solutions early on, while 4D models are used for site safety planning [15]. BIM has also been used to automate the detection and prevention of fall hazards, particularly at slab edges [87]. In addition, 4D BIM improves project management by enabling the visualisation, assessment, and prevention of risks throughout the project lifecycle. Combining BIM with tools such as online databases, virtual reality, and 4D schematics improves safety management [88].

Rey-Merchán et al. [46] and Park et al. [19] developed an on-site safety monitoring system that integrates BLE-based localisation, employing BIM for risk detection and cloud communication. The system identifies hazardous areas in the BIM model, either automatically or manually, and tracks the real-time location of workers to assess their exposure to risk [32]. It also ensures correct harness use in high-risk areas [31], with results shared via the cloud for effective safety management.

In the study developed by H.-J. Kim et al. [39], the worker's internal position was defined based on the smartphone's GPS, and in the BIM model, the safety manager created the fall risk map from a height. The location data obtained from the smartphone is mapped and displayed as a red dot, and the system sends an alert to the worker's smartphone, depending on the position.

The RTLS positioning system used in the study [42] consists of reference tags and anchors associated with workers and danger zones, which transmit information via wireless signals. The synchronised 3D model was used to receive the location data in real time and process the information to signal when a worker is in a danger zone previously defined in the model. This system allows an alert to be sent to the workers via the helmet-mounted tags when they approach a danger zone.

The studies [50,53,68] integrated BIM with computer vision to transform the information collected on site and visualise the potential risks that workers are exposed to at any given moment in the generated 3D model, known as the virtual safety model. When integrating monitoring technologies with BIM models, in order to verify the potential risks in the model, it is necessary to ensure that the construction model is up to date, i.e., that the digital twin corresponds to the progress of the work and that there are no discrepancies between the actual condition and the information in the BIM.

4.4. Research Findings

Summarising the results of the analysis of the selected documents, several real-time monitoring technologies can be used to improve occupational safety and health in construction.

- Real-time monitoring technologies are important for understanding the location of workers and selecting the most accurate technology, depending on the type of site (indoor or outdoor). In their study, Li et al. [76] presented the main indoor positioning technologies that are very promising and can enable a proactive approach to construction safety.
- The integration of different monitoring technologies can be beneficial, as it allows for filling the gaps that exist separately in each of the technologies [73,78]. However, this is an issue that is not addressed in the selected studies, so future research directions should focus on this issue.
- BIM is a tool that, as we already know, can contribute to safety management at all stages of a building's life. Some studies have analysed the possibility of integrating BIM with different types of tools for multifunctional applications. In fact, some studies aim to merge BIM with other technologies such as sensors, GPS, virtual reality tools, etc., specifically to develop proactive solutions. This is an aspect that represents a promising research trend to further develop and achieve an integrated Building Safety 4.0 environment [24].

4.5. Ethical Issues in the Use of Monitoring Technologies

From a legal perspective, employee monitoring is governed by various laws, most notably the General Data Protection Regulation (GDPR) in the European Union (EU), which sets strict standards for the processing of personal data. In addition, national health and safety regulations require companies to ensure the physical and mental well-being of their employees. However, real-time monitoring raises legal issues that need to be carefully considered.

The proposal suggests that employers should not be able to use consent (GDPR Art. 6(1)(a)) to justify data processing on the basis of an unequal relationship with employees. Furthermore, while health and safety legislation defines risk as the likelihood of injury in the event of an accident, artificial intelligence (AI) legislation also takes into account the severity of the injury. The key point is that the collection of data from workers and their limited capacity to consent poses risks that current legislation does not yet effectively address [89].

Real-time workplace monitoring for health and safety is permitted if it complies with the GDPR principles of proportionality, transparency, and data minimisation. Companies must avoid intrusive practices, handle data securely, and ensure that data collection is justified and respects workers' fundamental rights. Monitoring technologies help identify risks, assess their severity, and analyse worker behaviour, enabling employers to prevent hazards through direct action or guidance. AI and the Internet of things (IoT) enhance this by enabling rapid responses to unsafe behaviour, thereby improving workplace safety. However, increased technological control also increases employers' safety obligations and reduces workers' autonomy. Once safety measures are in place, reckless behaviour becomes a breach of contract, emphasising the worker's duty to comply [90].

4.6. Future Research Opportunities

Real-time detection and monitoring is rapidly advancing in fall protection technology, with recent studies focusing on models and systems to predict falls from height, but gaps remain in the integration of different technologies to monitor and prevent fall risks in real time.

While fall prevention mechanisms have been used in the construction industry for decades, the continued reliance on traditional methods has slowed innovation, highlighting the need for future research to create more versatile and smart systems for proactive fall prevention [91].

Computer vision is an emerging surveillance technology in the research. However, its ability to detect unsafe behaviour on construction sites is limited by technical challenges, in particular, the occlusion problem. To address these issues and improve the effectiveness of the model, the investigation of synchronised multi-camera systems is recommended [54].

Radio-based monitoring technologies integrated into the BIM model have generally demonstrated reliable performance. However, further improvements are needed, particularly in the selection of the risk zone boundaries and the geometric accuracy of the BIM and the risk zones. Keeping the building model and its status up to date is critical to the overall effectiveness of the system [19].

While BIM can bring significant safety benefits to construction, there are challenges in combining it with other technologies. Continued efforts are needed to advance knowledge and improve the use of BIM technologies to fully realise their potential benefits.

4.7. Limitations

This review has limitations, including language bias, as only studies published in English were included, and publication bias, as unpublished studies were excluded. Due to differences in the monitoring parameters addressed by each study, a direct comparison of the results was not possible, resulting in a descriptive summary of the techniques used in each study.

5. Conclusions

This systematic review, based on the PRISMA methodology [26,27], aimed to identify real-time monitoring technologies developed to reduce the risk of falls from height, a major cause of injury and death in the construction industry.

The studies show that real-time worker monitoring is based on wireless and computer vision technologies and can be integrated with BIM software for better risk management. It can be concluded that, given the positive results obtained in each of the studies, there is great potential for implementing these monitoring technologies in a construction context, contributing to safety on construction sites.

These monitoring technologies exhibit advantages, particularly in the real-time monitoring of the risks to which workers are exposed, which can be addressed before an accident occurs. They also display disadvantages, particularly concerning the privacy of the data/information collected when monitoring workers.

Finally, it was found that combining different technologies can be beneficial, allowing results to be achieved with greater precision and accuracy regarding worker positioning. However, none of the studies focused on the hybridisation of real-time monitoring technologies. Future work should, therefore, include different technologies for real-time monitoring of fall hazards and their integration with a construction BIM model to validate their applicability on a construction site.

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