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DIGITAL TWIN FOR SAFETY ON CONSTRUCTION SITE: A REAL TIME-TIME RISK MONITORING SYSTEM COMINING WEARABLE SENSORS AND 4D BIM

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Abstract

This paper presents the outcomes of an innovative safety project integrating Health and Safety standards, Building Information Modelling (BIM) and wearable sensors to address safety on construction sites. The paper presents a framework and a prototype that integrates 4D BIM and a real-time tracking sensing system. The 4D BIM virtually identifies and collects the data of hazard zones which is synchronized with the tracking-based sensing system and is used to monitor the access to and interactions with risky zones on construction sites. Real-time alerts are automatically triggered in case of unauthorised trespassing to proactively prevent accidents. The collected monitoring data are then visualised within the 4D BIM model, enabling stakeholders to identify trends and evaluate the effectiveness of safety measures. The integrated system was validated in a construction site and showcased a shift to proactive safety measures, improving hazard identification and control.

Introduction

Construction sites are widely considered one of the most hazardous work environments due to their constantly evolving and unpredictable nature, encompassing high-risk activities, and the frequent interaction between workers and machinery (Jin et al., 2020; Kulinan et al., 2024) The latest report from the Health and Safety Executive (HSE, 2023) documented a total of 135 fatal injuries in work-related accidents in Great Britain in the year 2022/23, 45 of which were within the construction sector, making it by far the leading sector in fatal accidents. The report also highlighted a total of 53,000 non-fatal injuries within the construction sector for the same year. One of the major causes of injuries and fatal accidents in construction sites is "unauthorised incursion" (Jin et al., 2020; Shuang et al., 2019). Unauthorised incursion refers to the entry or presence of an onsite person in an identified hazard zone without a permit, reflecting his role or competence relative to that zone. According to HSE, many contractors in the UK address this issue by employing traditional engineering controls from the hierarchy of controls, Figure 1, by providing workers with Personal Protective Equipment (PPE) and installing physical barriers (e.g., safety bollards, tapes, barricades, toe boards, signs, cones, etc.) to protect and isolate workers from hazards. Although traditional barriers can mitigate some of the risks on site, they are associated with several limitations. These include labourious and time-consuming installation, vulnerability to trespassing or destruction, and a lack of proactive and early warning mechanisms (Ding et al., 2022; Kulinan et al., 2024). Hence, over the last two decades, many researchers and industry practitioners have sought different ways to address such limitations and improve safety measures by proposing various digital technologies which is referred to in this study as an innovative measure, i.e., digital control, to the Hierarchy of Controls, (see Figure 1). These digital technologies include Building Information Modelling (BIM), IoT devices, extended reality, wearable and embedded sensors, and robotics for identifying and controlling onsite hazards.

These emerging technologies are integrated into construction safety management owing to their capabilities for automated hazard identification, real-time monitoring, proactive warnings, and data-driven decision-making. Although technologies in general contributed significantly to enhancing safety measures in construction sites, it remains difficult to meet high safety standards especially when these technologies are solely employed or not incorporated with safety standards and protocols (Jin et al., 2020; Wang et al., 2022). Therefore, this paper introduces an integrated safety system designed to overcome previous limitations, aiming to identify and control hazard zones, fostering mutual interaction between the virtual design model and the physical site.

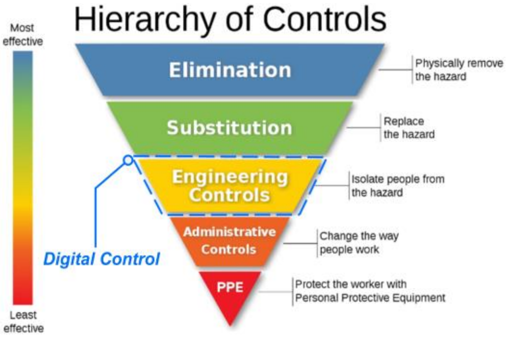


Figure 1. The Hierarchy of Controls Framework; with Digital Control integrated into the Engineering Control layer.

Related Studies

Various digitalization-based safety systems have been developed and introduced to enhance safety measures and prevent incidents in construction sites by identifying, monitoring, and controlling onsite hazards. Table 1 presents a summary of related studies and characterization of their safety systems to better highlight the innovation and contribution of our system. The characterization examines the studies based on several criteria that examine the level of automation, effectiveness, and responsiveness of the presented safety systems. The characterization examines the studies based on the below criteria that inspect the level of automation, effectiveness, and responsiveness of the presented safety systems.

- *Hazard identification mechanism* that investigates the type of technologies used to identify and highlight safety hazards whether during the design in virtual models or during construction on site. It also checks whether the project programme was considered as it is key to include the time dimension and the activities sequence when identifying hazards to be monitored. For instance, when identifying a hazard zone, its associated activities, and their start/end times should be available for the monitoring system to be activated/deactivated based on such data.

  In general hazard identification technologies include BIM, extended reality, and computer vision. BIM has proven to be an effective tool in safety management during the design phase by enabling designers and planners to highlight safety hazards in the design models and propose mitigations. However, BIM independently lacks dynamic data from the construction site that should be streamed in real-time to accurately depict what is currently happening on site (Kulinan et al., 2024). Therefore, BIM by itself is not sufficient for managing safety and requires the integration of IoT and sensing devices to provide timely data during construction.
  Extended Reality (XR) technologies have also been widely adopted in safety management to provide an immersive and interactive environment to identify and visualise onsite risks (Wu et al., 2022). Their adoption has mainly been for providing safety training to construction workers where safety instructions and guidelines are displayed for identified hazards, enabling the worker to manage onsite hazards effectively and interactively.

  Other technologies have also been used to identify onsite hazards including computer vision-based approaches. Many researchers proposed vision-based safety systems that collect and process visual data to recognise onsite risky behaviours of construction workers or equipment. Despite their automated approach to identifying potential hazards, computer vision techniques are limited to certain safety scenarios and types of objects that were trained to detect and recognise (Kulinan et al., 2024). Furthermore, these systems require a clear and uninterrupted visual data stream which in many construction sites is not easy to ensure due to their dynamic nature with various moving parts.
- *Hazard monitoring mechanism*, looking into the types of technologies used to collect and process data from the construction site and whether this mechanism is fully automated or not. There is a wide array of different sensing and IoT devices adopted in the literature depending on the type of data that needs to be collected. For example, in most safety applications, location data of onsite personnel or equipment is mainly needed, and it is generally collected using position sensors (e.g., GPS). In other applications where the motion data of equipment is required, motion sensors (e.g., IMU) are mainly used. In some studies, visual sensors (e.g., CCTV cameras) are favoured to acquire images or video streams that can be used to monitor hazard zones.
- *Hazard controlling mechanism*, ensuring the safety system leverages real-time and automated controlling mechanism that alerts people from potential hazards and proactively prevents injuries or accidents. For instance, when an unauthorized incursion occurs, it is expected for the system to trigger a fully automated warning in real time to alert the unauthorized person as well as HSE managers. This criterion also investigates whether a system employs visualisations that report and present monitoring data and analysed metrics (e.g., zone interactions metrics) in a timely manner. It also examines whether a learning feedback loop is integrated into the safety system that ensures a continuous learning loop based on the monitoring information from previous reports to enhance the safety measures of future onsite hazards.
- *Integration of Design and construction measures* which checks whether a given study integrated the safety measures during the design phase with those applied during the construction phase and if there is a feedback loop from the construction to the design that can enhance the safety planning of future sites.

As illustrated in Table 1, there is a gap in integrating all these elements into a unified system able to identify, monitor, and control on-site hazards in an automated and proactive manner while ensuring a learning/improving feedback loop between the design and construction.

Table 1. A summary and characterisation criteria of key related studies

Study	Hazard identification			Hazard Monitoring		Hazard Control			Integrating design and construction measures	Application description
	4D BIM	XR	Other	IoT sensing	Automated data stream	Real-time alert/warning	data/metrics visualisation	Feedback loop		
(Jin et al., 2020)				●	●	●	●	●		Employing IoT-based locating and alarming system for unauthorised incursions to risky workspaces in a construction site.
(Hossain et al., 2023)	●			●	●	●	●			GPS-based mobile application for tracking and alerting workers approaching predetermined hazard zones.
(Wu et al., 2022)	●	●		●		●	●	●		Integrating deep learning and mixed reality to generate real-time visual warnings.
(Chung et al., 2023)				●	●	●		●		RFID-based system for monitoring and alerting onsite personnel
(Liang & Liu, 2022)	●			●		●		●		BIM and IoT technologies are proposed to develop a safety risk warning system for underground projects.
(Kulinan et al., 2024)	●			●	●		●			Integrating BIM and computer vision for real-time tracking of construction workers for safety directions.
(Ding et al., 2022)	●			●	●	●	●			IoT-based BIM safety system for identifying and monitoring energy hazards in petrochemical construction.
(Zhang et al., 2023)				●	●	●				RFID-based system for preventing hazard zone incursion through real-time warning.
(Jiang et al., 2021)	●			●	●	●	●	●		A cyber-physical system for identifying hazards in virtual models and monitoring them using IoT sensing and networking devices
(Hong & Teizer, 2024)			●	●			●	●		Using spatial-temporal data of construction workers to derive behavioural patterns and predict potential hazard zones.
(Tran et al., 2021)	●		●						●	Integrating BIM-based safety planning and image stitching for hazard zone identification in construction sites.
(Kojima et al., 2020)				●	●	●	●	●		Bluetooth-based monitoring and warning system to control human-machine interaction in tunnelling sites.
This study	●			●	●	●	●	●	●	Integrating H&S standards, BIM, and wearable sensors for identifying and controlling onsite hazards.

Research Methodology

This research project was conducted as part of the Discovering Safety initiatives delivered by the Health and Safety Executive (HSE) in the UK. The main aim was to integrate current Health and Safety (H&S) standards, BIM technology, and advanced wearable sensing systems for enhancing safety measures during both the design and construction phases while maintaining a learning/improvement feedback loop between the two.

To achieve this aim, a conceptualized integrated safety framework was developed that incorporates safety measures during the design and construction following the "plan, do, check, and act (PDCA)" followed by the HSE and according to H&S standards. This system was developed with continuous feeding input from key industrial stakeholders including project owners, designers, contractors, HSE representatives, and technology suppliers. The developed framework also presents the integration workflow between the two technologies (i.e., BIM and wearable sensors) that will be employed to identify and manage safety hazards during both phases. In this project, the SafetiBase system provided by 3D Repo was used to identify and capture hazards within the 4D BIM model while the sensing system was used to monitor and control the identified hazards. The developed framework was later implemented in a real construction site using both SafetiBase and Plinx platforms to validate its level of effectiveness and responsiveness to prevent onsite incidents and enhance safety measures.

Construction Safety Integrated Framework

Figure 2 presents the construction safety framework, integrating the BIM technology and the sensing system for managing safety during the design and construction phases. In the design phase, 4D BIM models play a key role in hazard identification within the construction sequence following the PAS 1192-6 standard, as illustrated in Figure 3a. Pre-approved treatment strategies following H&S standards and contractors' best practices are then placed to address those hazards. Where possible, identified hazards should be eliminated or substituted by changes to the building sequence following the hierarchy of controls (recall Figure 1). There are, however, lots of instances where this is not practical and engineering controls must be employed to ensure the safety of the working area during the construction phase.

For each identified hazard, a zone is marked virtually within the BIM model encompassing that hazard (Figure 3b). For each identified hazard, detailed information, including XYZ coordinates, project reference point, and the start and end times of associated activities, is gathered by the Plinx broker through 3D Repo's API. These XYZ coordinates are then converted to WGS84 Lat/Lon by the broker for compatibility within the Plinx system. Plinx effectively activates and deactivates the designated zones at the specified times. The Plinx platform hosts metadata from the risk treatment ticket, involving zone type, purpose, and additional information available in the treatment notes.

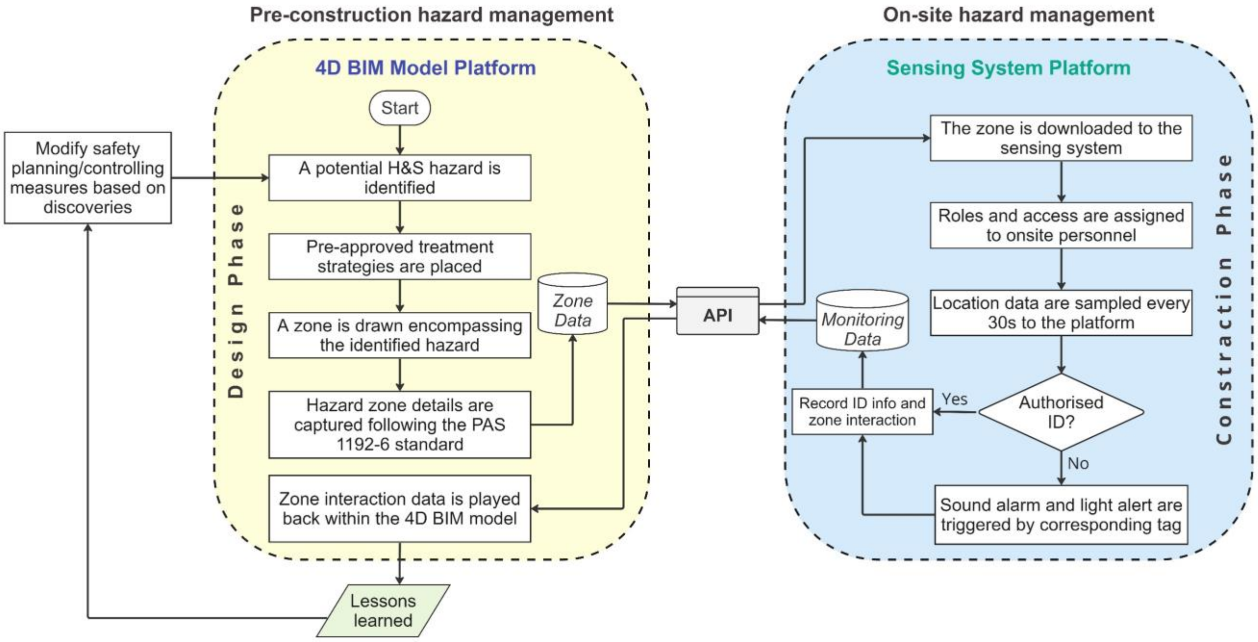
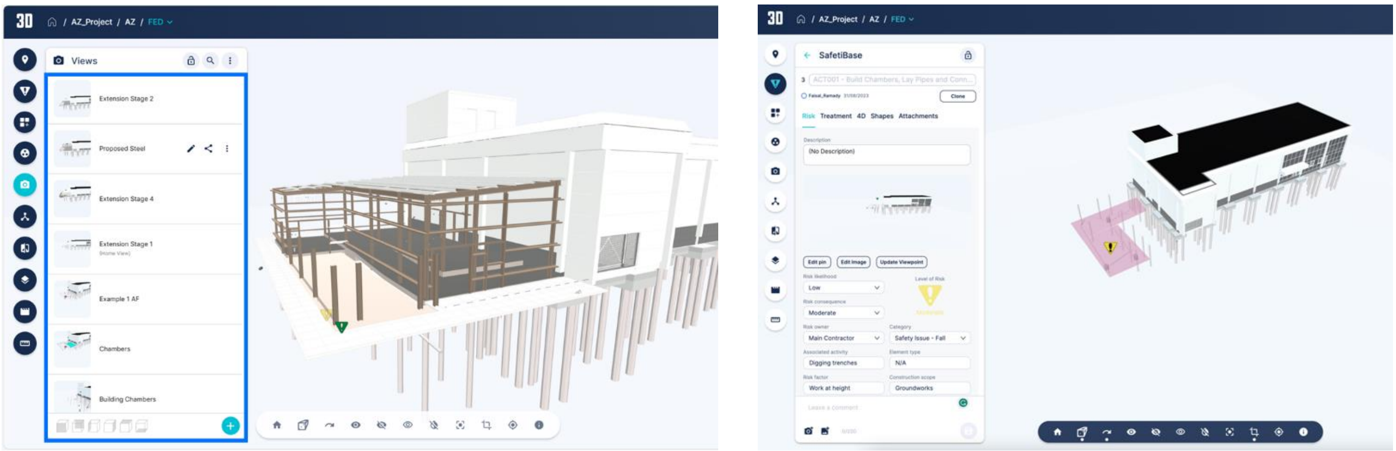


Figure 2. The proposed integrated safety system as a bi-platform management system



3 ACT001 - Build Chambers, Lay Pipes and Conn...

Description: (No Description)

Risk likelihood: Low

Risk consequence: Moderate

Risk owner: Main Contractor

Category: Safety Issue - Fall

Associated activity: Digging trenches

Element type: N/A

Risk factor: Work at height

Construction scope: Groundworks

(a) **(b)**

Figure 3. Identifying H&S risks virtually in a 4D BIM model using 3D Repo platform: (a) identified hazard activities within the construction sequence, (b) marking up a hazard zone associated with a drainage activity as an example.

Upon receiving zone data, Plinx establishes a connection with its corresponding physical wearable sensors. Before each construction shift, access permits are assigned to onsite personnel based on their roles and competencies, specifying permissions for entry and operation within the designated zone intended to be monitored. Unauthorised access triggers real-time alerts through the automatically activated sensors. The Plinx platform offers real-time visualisation of all monitoring data and zone interactions.

At the end of each shift, zone interaction data, both authorised and unauthorised entries, is promptly transmitted to 3D Repo via API. This includes location data recorded every 30 seconds, accessible through an API call typically conducted at the end of each working day. Plinx ensures the conversion of this data to XYZ coordinates before export. Within the 3D Repo environment, the movement and interactions within zones can be played back onto the BIM model, providing a contextual reference to the initially created zones. Doing so enables reflecting on the effectiveness of the current safety strategies and enhancing the safety planning and management of future hazard zones. This iterative process not only reinforces the practical implementation of integrated systems but also supports the overall efficacy of the H&S risk management framework.

Case Study

To validate and measure the effectiveness and responsiveness of the developed integrated safety framework, an on-site case study was implemented with the main intention of acquiring authentic, real-world data from a dynamic construction site. The on-site trial took place at AstraZeneca's quality assurance building project.

Hazard Zone Setup: AstraZeneca's 4D BIM model was imported into the SafetiBase platform for hazards to be identified and captured. Initially, four construction activities with potential risks were identified — footings excavation, drainage chamber installation, steel erection, and utility connection into the main road. However, given the compact site and the diverse expertise of the chosen subcontractors, establishing safety zones for all these activities based on roles and competencies posed a significant challenge. Consequently, only the steel erection task, which was executed by a specialised team, was selected to be monitored onsite (Figure 4). A safety zone was established around its locations with its hazard details captured in the BIM model following the PAS 1192-6 standard. The zone and its data were then extracted from SafetiBase by the API and sent to the Plinx platform to be monitored on-site during construction.

On the construction site, the WGS84 coordinates of the zone are precisely mapped using a survey rover, (Figure 5a). The survey rover outputs a GEOJSON file which is then uploaded directly to the Plinx platform to validate its alignment with the safety zone plotted in SafetiBase.

Figure 4. The safety zone selected around the steel erecting work to be monitored and controlled.

(a) **(b)** **(c)** **(d)**

Figure 5. The sensing system: (a) a GNSS Rover, (b) RFID card, (c) charging and allocation station, (d) wearable sensor connected to a safety helmet.

Sensing System Setup: The sensing system used to monitor the hazard zone was supplied by Plinx. The wearable sensors were connected to JSP construction helmets as illustrated in Figure 5d. Plinx RFID cards were used to assign operative roles and competencies of onsite personnel against their card IDs', see Figure 5b. Site operatives then scan these RFID cards to receive a sensor with personalised zone access based on their assigned roles relative to the zone.

Safety Zone Monitoring: Following the sensing system set-up, the safety zone around the steel erection work was monitored for one week. The wearable sensors and cards were assigned at the beginning of the working shifts. The wearable sensors transmitted the location data of onsite personnel every 30 seconds. These data points were visually represented on the platform as green dots, as illustrated in Figure 6. The monitoring system was intricately designed to generate alerts in the event of unauthorised individuals entering the designated zone. To assess the system's responsiveness and reaction time, deliberate unauthorised interactions were induced within specific areas of the monitored zone. Upon the entry of unauthorised individuals, their sensors emitted audible beeps and vibrations. The locations of these breaches were then visually depicted as dark blue dots (Figure 6).

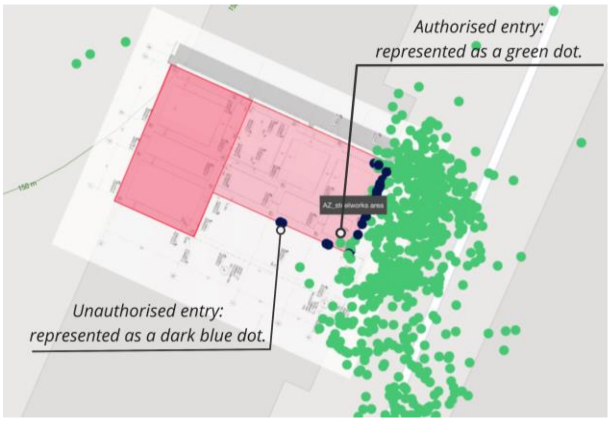
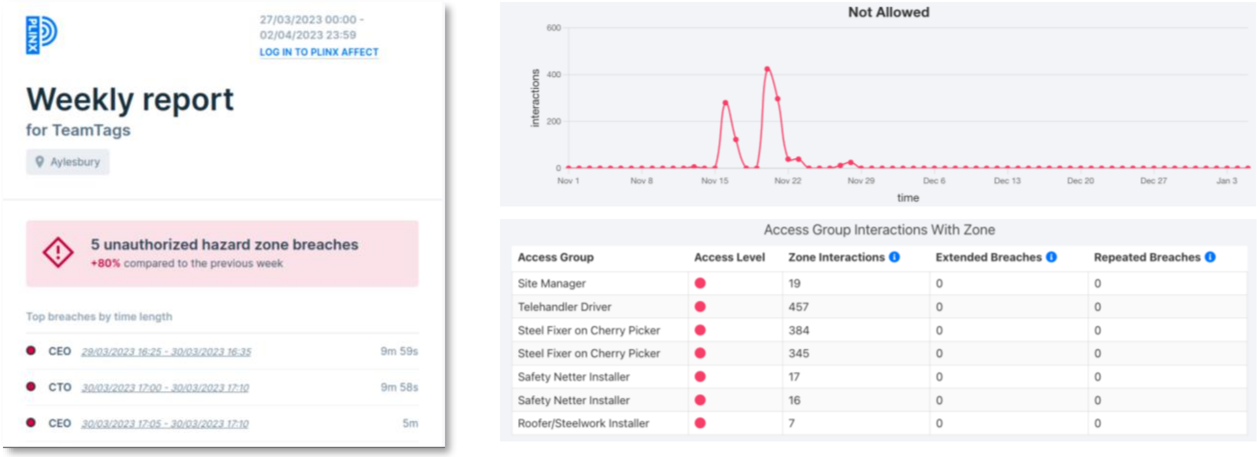


Figure 6. Zone interaction data for a week-period monitoring

All zone interaction data are recorded and presented in a comprehensive weekly report, see Figure 7. This report includes details such as the number of authorised/unauthorised entries and associated information, including personnel ID and role, date, and time of entry, as well as the duration of their presence within the zone. The gathered monitoring data are used to enhance week-on-week management strategies of safety zones by playing it within the 4D BIM model, as illustrated in Figure 8. More significantly, it plays a crucial role in providing insightful feedback to planners and designers, offering valuable insights into the efficiency of implemented preventive measures. This feedback loop ensures an ongoing enhancement of safety protocols, fostering a dynamic and responsive approach to maintaining and improving overall safety standards.

Results and Discussion

Trial Impact: This work has demonstrated the successful implementation of the developed safety framework integrating H&S standards with digital technologies for identifying and managing hazards on construction sites. The integration of digital technologies has significantly enhanced construction safety through proactive hazard identification and management. Unlike traditional reactive approaches, the digital control system, equipped with automated sensing and monitoring, predicts and prevents potential hazards in real-time. This ensures not only the effectiveness of safety measures but also responsiveness to dynamic site conditions. The system's proactive alerting further strengthens safety by triggering immediate responses to unauthorised individuals breaching safety zones, reducing the risk of accidents. The monitoring system has a detection accuracy within a 50 cm radius, significantly enhancing safety by triggering a warning when a worker approaches the zone at a proximity of just 50 cm at a walking speed of 4 mph. This level of precision surpasses the accuracy of systems documented in previous studies. For example, the system presented by (Jin et al., 2020) gets triggered only when a worker is within a 200 cm distance. Additionally, our system demonstrates real-time responsiveness, with an estimated average reaction time of just 0.3 seconds.



27/03/2023 00:00 - 02/04/2023 23:59

LOG IN TO PLINX AFFECT

Weekly report

for TeamTags

Aylesbury

5 unauthorized hazard zone breaches

+80% compared to the previous week

Top breaches by time length

CEO	29/03/2023 16:25 - 30/03/2023 16:35	9m 59s
CTO	30/03/2023 17:00 - 30/03/2023 17:10	9m 58s
CEO	30/03/2023 17:05 - 30/03/2023 17:10	5m

Access Group Interactions With Zone

Access Group	Access Level	Zone Interactions	Extended Breaches	Repeated Breaches
Site Manager	●	19	0	0
Telehandler Driver	●	457	0	0
Steel Fixer on Cherry Picker	●	384	0	0
Steel Fixer on Cherry Picker	●	345	0	0
Safety Netter Installer	●	17	0	0
Safety Netter Installer	●	16	0	0
Roofer/Steelwork Installer	●	7	0	0

(a) **(b)**

Figure 7. Recorded unauthorised incursions to the zone: (a) an example of a weekly report summary, and (b) data visualisations of the steel work zone interactions over the monitoring period.

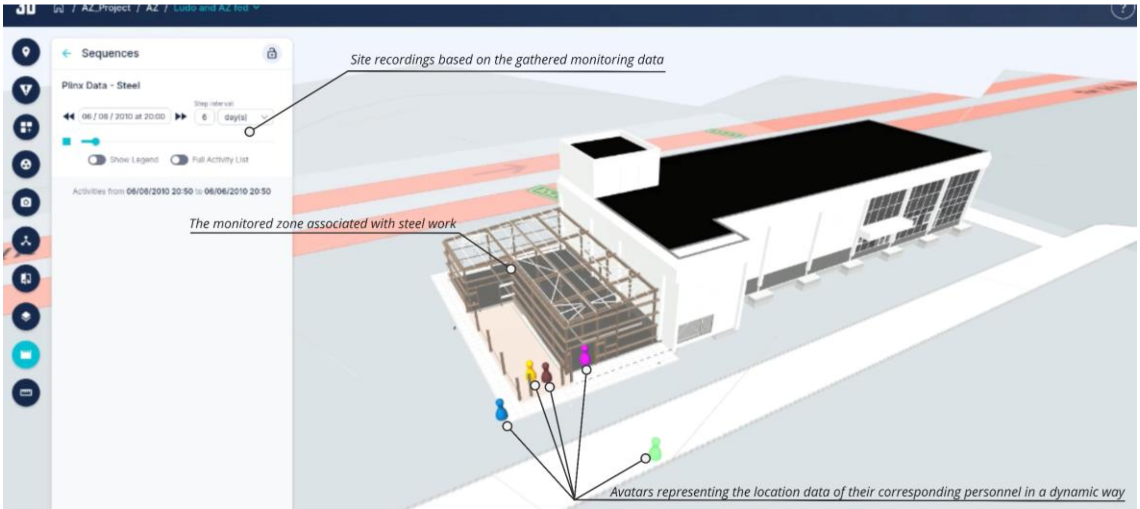


Figure 8. A screenshot from a video displaying the location data gathered during the zone monitoring within the 4D BIM model.

Moreover, the developed system extends data visualisation into the 4D BIM model, providing a comprehensive understanding of the construction site layout and potential hazards. This allows stakeholders to analyse safety data over time, identify trends, and make informed decisions for targeted improvements. The feedback loop in the system plays a crucial role in refining safety protocols by providing continuous, data-driven insights. Unlike traditional post-incident analysis, this system fosters a proactive safety culture, emphasizing ongoing refinement and optimization based on timely feedback.

Limitations and Future Recommendations: While this trial has shown promising advancements in safety management by integrating BIM and monitoring-based sensing, it is crucial to recognise the challenges and limitations faced during implementation. These insights are valuable for refining the system and optimizing its performance in larger-scale construction scenarios. One key challenge involved difficulties in obtaining and applying pre-approved treatment strategies for establishing and marking safety zones. This issue is widespread among contractors due to the absence of a standardized zonal control framework specifying attributes of a given zone based on the construction activity associated with it. The current process has a limitation where the shape drawn in SafetiBase is a freeform polygon. While this provides flexibility, it may lead to discrepancies between the digital zone and the physical segregation on site. A preferable solution would involve the system applying standardized rules to the highlighted hazard, assisting designers in comprehending the spatial impact and aiding the site team in deploying physical barriers more effectively.

It is vital to automatically align safety zones with planned activities to prevent sensor alerts from inaccurately triggering and misrepresenting actual locations. The plan involves developing a customised SafetyZone interface within 3D Repo to enable safety managers to authorise and restrict zone access to operatives, machines, or groups seamlessly as part of the system workflow. It is also worth noting that the deployment of sensing technologies, particularly monitoring personnel through wearable sensors and collecting location data, raises privacy and data security concerns. Achieving a careful balance between enhancing safety and respecting individual privacy rights is essential. Implementing robust data security measures is crucial for ethical and legal considerations, ensuring responsible use of the collected data and compliance with privacy regulations.

Conclusion

This work presented a construction safety framework that integrates H&S standards with digital technologies to enhance safety planning and management in construction sites. This innovative approach represents a shift from reactive to proactive safety measures. Utilizing BIM for virtual hazard identification and real-time monitoring through sensing technology, the integrated system predicts and prevents potential hazards, reducing the likelihood of accidents. The developed system also enables visualising monitoring data within the 4D BIM model, offering stakeholders a comprehensive understanding of the site and supporting continuous improvement through a dynamic feedback loop between the design and construction phases.

Acknowledgements

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