Innovation Trial: Integrating Live Monitoring of Site-based Sensors with 3D Models to Improve Health and Safety on Construction Sites

Case Study

Author(s): Wahib Saif, Tommy Williams, Jozef Dobos, Charence Wong, Gordon Crick.

Report number: CRL IT 001

Disclaimer and Acknowledgments

This document and the work it describes was conducted as part of Discovering Safety, an initiative aiming to enhance the health and safety risk management using insights from data. The information contained herein, included opinions, conclusions, and recommendations, do not necessarily represent the official policy perspectives of the Health and Safety Executive (HSE) or Lloyd's Register Foundation. This report stands as an independent contribution to the ongoing efforts to advance health and safety within the construction sector.

The project team extends sincere gratitude to the Lloyd’s Register Foundation for funding Discovering Safety. Special appreciation is also extended to HSE for providing data resources. We express our thanks to AstraZeneca for their support in hosting the Trial, and to Dalkia as Main Contractor on site for resourcing and enabling the trial through their supply chain.

Key Messages

This innovation trial introduced the concept of digital control that leverages digital technologies to improve workers health and safety in construction sites. Discovering Safety, a programme of work led by HSE, has funded this trial as part of the Construction Risk Library project within it. It is a forward look, to see how the next generation of design tools can work together better to enhance safety zone procedures.

This concept was demonstrated through an innovative integration of Building Information Modelling (BIM) and wearable sensors to identify hazard zones in virtual models and monitor them in physical construction sites.

The Key Messages are:

1) Although the technology of creating and visualising safety data in BIM models has been in existence for some time, as has the employment of on-site sensors, the ability to achieve mutual interaction between the virtual design model and the physical construction site is a new achievement through this trial.

2) This trial reinforces the importance of a collaborative approach between Client, Designers, Principal Designer and the Principal Contractor with their supply chain. To achieve success in real time monitoring and creating feedback through the BIM model, the co-operation of individual workers is necessary.

3) This report demonstrates the feasibility of mapping out or delineating safety zones on a BIM model, applying these as a “geofence” on a site using sensor and GIS technology, and then monitoring actual incursions into the safety zone in real time. Work now needs to be done to embed more effective zonal protection procedures through the industry.

4) Early 4D modelling is a great aid, and even may be an essential prerequisite to getting the best outcomes from live monitoring of safety zones.

5) Careful consideration needs to be given to the stage of the project at which the technology is applied. Designers need to fully understand how models can be used as a basis for an effective feedback loop from site back to the design team.

6) To get the best from the technology a broad mix of technical skills is required – the trial shows that learning can be swift and effective to deploy the techniques used.

Executive Summary

This report presents the outcomes of an innovative safety trial, integrating Building Information Modelling (BIM) technology with wearable sensors to enhance safety on construction sites. The trial was conducted at AstraZeneca's QAB extension project in Macclesfield, focusing on identifying and monitoring hazardous zones in an automated and proactive manner.

Discovering safety is funded by Lloyds Register Foundation and led by the Health and Safety Executive. Discovering Safety includes a range of projects which aim to improve the way digital data is used for improving health and safety, and to improve the use of digital tools which help to manage risk well. One Project within Discovering Safety is the Construction Risk Library, and it this project which is vitally concerned with the way risks are described and managed in construction design, and with how risk treatments such as safety zones are deployed. This trial forms a key part of this project. It is a forward look, to see how the next generation of design tools can work together better to enhance safety zone procedures.

The trial's implementation involved the setup of safety zones using a 3D BIM model within the SafetiBase platform provided by 3D Repo, coupled with the deployment of a sensing system supplied by Plinx. Safety zone access was monitored through wearable sensors, and the collected data were integrated into the BIM model. Through this integrated system, the trial demonstrated the digital control paradigm that proactively identifies and manages hazards, offering real-time monitoring and feedback loops.

The integration showcases a tangible shift from reactive to proactive safety measures. The system's real-time monitoring and automated alerting mechanisms demonstrated in a proof of concept that it is realistic to expect significantly improved hazard identification procedures, along with direct real time feedback to the site office of incursions into safety zones. These measures will improve timeliness of management decisions to address problems and reduce the likelihood of a failure of a safety zone to separate the hazard from a vulnerable target. The digital control of data visualisation within the BIM model, will facilitate comprehensive analysis and informed decision-making by designers, construction planners and site managers.

Despite the successes, challenges and limitations were encountered, including integration complexity, accuracy and calibration issues, user adaptation, privacy concerns, and cost implications. These challenges provided valuable insights, leading to recommendations for refining the system. Lessons learned underscored the importance of categorising safety zones, automating zone updating workflows, introducing people and machine zoning, and optimising the utilisation of shapes functionality in 3D Repo.

In conclusion, the trial successfully demonstrated the potential of integrating BIM and monitoring-based sensing technologies for construction site safety. The findings highlight the need for ongoing refinement and optimisation, emphasising the importance of a collaborative approach which involves the whole project team, from the Client through to the sub-contractor. The report concludes with a forward-looking perspective, highlighting the lessons learned and providing recommendations for the future deployment of this innovative safety management system in construction contexts.

Content

1. Introduction

1.1. Background

Construction projects have long been characterised by their dynamic and unpredictable nature, introducing inherent challenges to the health and safety of workers on construction sites. As the construction industry continues to evolve, there has been a growing recognition of the need for technologies to augment traditional safety measures. Over the past two decades, there have been notable advancements in Health and Safety (HEALTH AND SAFETY) performance throughout Great Britain (GB) highlighted by the adoption of different technologies including Building Information Modelling (BIM), wearable technologies, extended reality, and robotics. However, much more work is needed to realise the benefits of these technologies.

Recent data from the Health and Safety Executive (HSE) reveals that In Construction there were 45 fatal injuries to workers in 2022/23 in comparison with the annual average number of 37 fatalities for 2018/19-2022/23. In addition, there were 3 fatal injuries to members of the public in 2022/23p. The fatal injury rate in Construction is 1.72 per 100,000 workers, this is around 4.2 times all industry rate. If you consider occupational health, in a single year in Construction, there were an estimated 69,000 workers suffering from work-related ill health, (new or long-standing) and 54% of these were from musculoskeletal disorders. These figures do not include those forced to retire from work in the industry. The implications of these incidents extend beyond the affected individuals, affecting their families, employers, the government, and society at large. For example, of the estimated deaths due to occupational cancer in 2005, around 3,700 were attributed to past work in construction industries, and about 70% of these cases were caused by past exposure to asbestos, (associated with lung cancer and mesothelioma).

Construction workers are faced with a diverse range of health and safety risks, ranging from the potential for falls and structural collapses to exposure to hazardous substances and noise pollution. For example, around 51% of deaths over a five-year period were classified as Falls from a height, The financial toll on GB society attributed to work-related injuries and illnesses in the construction sector is significant. The total cost in 2021/22 is estimated at £1.3 billion, (95% confidence interval £1,011M - £1,668M). To reduce these losses, and address what are generally well known health and safety risks in construction projects requires a comprehensive approach that integrates advanced technologies and traditional approaches to compliance with safety regulations in order to ensure the well-being of workers on construction sites.

As a part of its mission to address such challenges and enhance safety measures on job sites, Discovering Safety, delivered by the HSE, and in collaboration with industry innovators lunched this trial that integrates safety regulations, BIM technology, and a network of sensors to identify and monitor safety zones on site and proactively prevent accidents.

1.2. Discovering Safety

Discovering Safety is a five-year programme being delivered by HSE and funded by the Lloyd's Register Foundation. Collaborating with industry, academia, and governments globally, Discovering Safety prioritises the development of new techniques for data analysis, with the goal of preventing future accidents. It also focuses on creating a global knowledge resource, incorporating comprehensive accident and incident data spanning 40 years. The aim is to develop a research environment to discover innovative ways to utilise HEALTH AND SAFETY data, contributing to a safer working world through international training, education, and practical solutions.

For the past two years, the programme has had a workstream addressing the construction sector. This has consisted of two Projects, the first addressing the need to develop better Leading indicators for monitoring performance in health and safety on projects, the second, The Construction Risk Library, has developed data sets to describe Risk Scenarios in design, and how these can be linked to preventive risk treatments. The Construction Risk Library team has led this trial. Working with forward looking Clients /designers and contractors. The aim of the trial is to demonstrate how safety regulations and digital technologies can be applied together to identify and monitor safety zones in construction sites in order to proactively prevent onsite accidents.

1.3. The Innovation Trial

1.3.1. Aim and Expected Deliverables

This innovation trial aimed to further improve safety measures on construction sites through an innovative integration of the existing HEALTH AND SAFETY risk identification and mitigation workflow from 3D models with on-site sensing technologies to identify and monitor safety zones. The aim was to demonstrate this integration by employing two digital systems: first is the SafetiBase system provided by 3D Repo to upload BIM models and visually identify HEALTH AND SAFETY risks. With this system, the identified safety zones can be marked-up and pre-approved mitigation strategies can be placed before the construction activities are carried out. The second system is an on-site sensor-based monitoring system supplied by Plinx that was utilised to monitor the identified risk zones and alert site operatives in real time in case of any unauthorised incursion to proactively prevent any potential accidents.

Although the technology of creating and visualising safety data in BIM models has been in existence for some time, as has the employment of on-site sensors, the ability to achieve mutual interaction between the virtual design model and the physical construction site has not yet been demonstrated. In this context, the integration of the BIM model and sensing networks emerges as a promising innovation to enhance safety protocols and mitigate risks for construction workers. Therefore, this trial is expected to deliver the following main outputs:

1. Showcase the viability of safety zones, planned in advance of work starting, on a construction site during construction.
2. Demonstrate how the data collected by on-site sensors can be visualised and analysed in a BIM model via a playback scenario. Doing so can offer valuable insights to guide future decisions for site planners.
3. Provide a basis for enhancing safety standards and generating guidance and best practice for the construction sector, in particular by enhancing analysis of the hierarchy of controls.
4. Contribute to the body of knowledge within HSE about the effectiveness of digital tools in the construction sector.
5. Contribute to enhancing health, safety, and productivity in construction practices by reducing delays and project cost resulting from on-site accidents.

1.3.2. Partnerships and Roles

Discovering Safety initiated this safety trial as part of its development of a Construction Risk Library, led by the HSE Construction Division and funded by the Lloyd's Register Foundation. AstraZeneca, an existing partner, offered to host this trial on a project they were already planning, a Quality Assurance Building (QAB) in Macclesfield. Discovering Safety has already conducted a case study in collaboration with AstraZeneca, focusing on the application of SafetiBase (3D Repo) to visualise construction safety risks in the design phase of the same QAB Extension project (accessible here). Therefore, this new trial represents a natural progression and extension of this collaborative efforts.

This trial builds upon a five-way partnership involving Discovering Safety, AstraZeneca's construction team, on-site support from Dalkia—the principal contractor appointed by AstraZeneca, and the two technology suppliers, Asite 3D Repo and Plinx. Plinx has also collaborated with Discovering Safety previously in developing a regulatory sandbox case study (accessible here). The findings from the sandbox case study as well as the previous SafetiBase's trial have fed into this trial. Table 1 summarises the role and responsibilities of each partner in this innovative trial. This trial intends to engage the professional interest of all the parties involved including the client, designer, contractor, and site-based staff engaged in the design and construction of this project to highlight and adopt new ways of harnessing digital technology to improve health and safety outcomes.

Table 1. A summary of the roles and responsibilities of the partners involved in this innovative trial.

Partner	Role and Responsibilities	Represented by	Contact
Discovering Safety	A five-year programme, funded by Lloyds Register Foundation and delivered by HSE. Responsible for organising and overseeing the overall execution of this innovative trial.	Gordon Crick	GORDON.crick@hse.gov.uk
AstraZeneca	The AstraZeneca construction team represents the client organisation and offered to host and actively support the implementation of this trial on their extension project of their QAB in Macclesfield.	David Ayres Brian Street	David.Ayres@astrazeneca.com Brian.street1@astrazeneca.com

Dalkia	The main contractor appointed by AstraZeneca and responsible for building the new extension for the AstraZeneca's QAB in Macclesfield and providing on-site support for implementing this trial.	Nick Hyde	nick.hyde@dalkia.co.uk
Plinx	A technology company responsible for providing and deploying a network of sensors to monitor and manage safety zones on site.	Tommy Williams	Tommy@plinx.io
Asite 3D Repo	A BIM technology company responsible for facilitating the integration of sensors with BIM models, and feedback mechanisms using their established SafetiBase platform.	Jozef Dobos	jdobos@asite.com

1.3.3. Ethics, Privacy and Data Protection

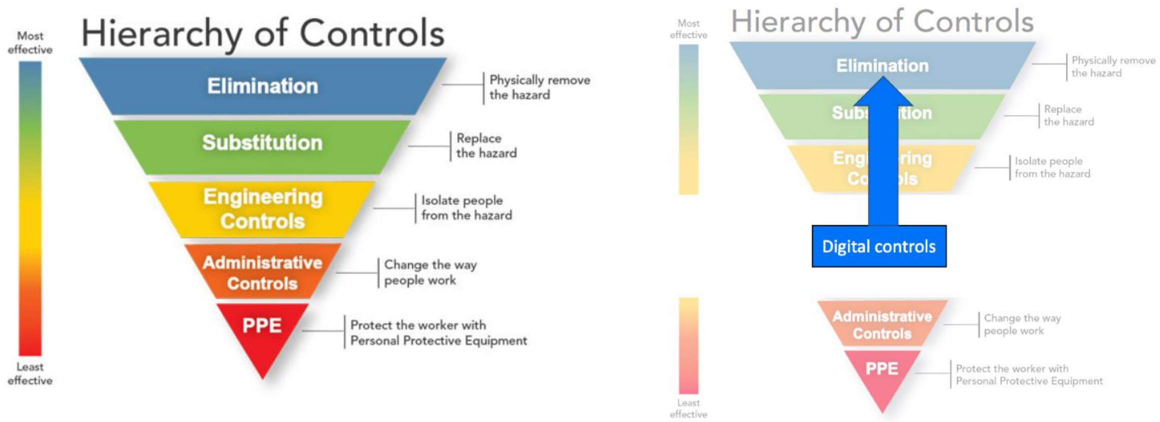
For this trial, additional equipment and data collection procedures are introduced which require considerations towards the impact upon subjects, the trial site, and project partners. The overall aim of this trial is to further improve safety measures on construction sites through the use of innovative technologies. A key advantage of the solution is the helmet-worn sensors are attached to safety helmets used by subjects on the construction site and as a result does not remove any safety equipment already in use. Furthermore, the wearable sensors also provide additional safety information to the user through alerts. To ensure privacy and data protection, no personally identifiable information of the participating trial subjects is included in the data processing pipeline. In agreement with the main contractor, Dalkia, training and information about the equipment and trial were provided and no significant changes to existing workflows on the construction site were introduced.

2. Methods

This section outlines the systematic approach employed to conduct this trial. Firstly, a conceptualised workflow was developed, illustrating the sequence of identifying and managing safety risks throughout both the design and construction phases. Subsequently, an integration framework is introduced to ensure seamless integration and data exchange between the two technologies (i.e., the SafetiBase system provided by 3D Repo and the sensor-based monitoring system supplied by Plinx). Finally, the case study implementation on a construction site is presented.

2.1. Digital Control Workflow

The Hierarchy of Controls, as depicted in Figure 1 (a), stands as a widely acknowledged framework that emphasises the precedence of proactive measures in hazard prevention. However, Discovering Safety, has reassessed the traditional triangle by incorporating the “Digital Control” layer, as illustrated in Figure 1 (b), introducing a new dimension that leverages the employment of digital technologies. Digital control will enable a more data-driven and proactive safety management approach by exploiting data sensing and 3D modelling technologies as it will be demonstrated in this trial. This data-driven approach will also enable learning from previous scenarios, allowing construction companies to deploy more effective measures, prioritising treatments higher up the Hierarchy of Controls.



(a) (b)

Figure 1. The Hierarchy of Controls Framework: (a) its traditional construct, and (b) a revised version, introducing Digital Control

Figure 2 illustrates the workflow that presents the sequential processes of digital control, incorporating the pre-construction hazard management during the design phase and the on-site management during the construction phase. Introducing digital controls as a supplement to enhance existing engineering controls, provides a way of analysing and improving the way workers interact and communicate with hardware controls, such as gates and fenced barriers. In the following list of potential safety benefits – only the first two were tested on this first proof of concept trial;

1) A worker wearing a digital zonal sensor and actuator can be warned audibly if they enter a zone they are not authorised to enter.
2) A worker entering a safety zone around a working machine can be audibly warned, and the driver alerted.
3) A worker could use a device such as a smart phone to obtain further information about a safety zone following an alert, or entry into a zone through an established gate or entry point.
4) A higher level of protection can be achieved if potentially harmful energy sources can be automatically limited or stopped if an unauthorised worker enters a safety zone.

For both the Pre-construction phase, and the Construction phase, defined processes and associated actions are presented as follows:

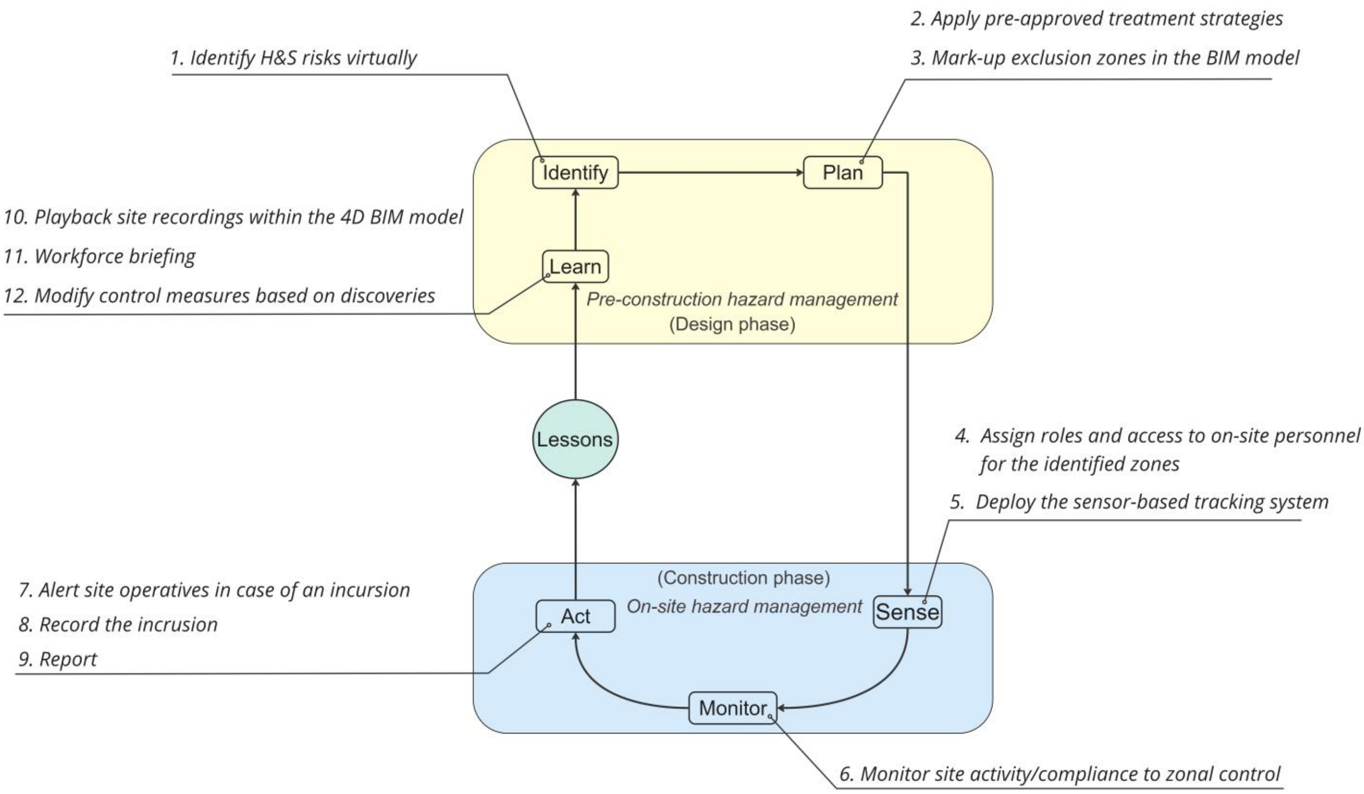


Figure 2. The safety workflow depicting the closed loop sequence of risk management processes during the design and construction phases.

2.1.1. Pre-Construction Zone Management (Design Phase)

The first step during the design phase is to identify any potential hazard in the building sequence within the BIM model. The space and time of the identified hazards should be highlighted in the model as presented in Figure 3. Pre-approved treatment strategies in accordance with HEALTH AND SAFETY standards and contractor bet practice should then be 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. 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.

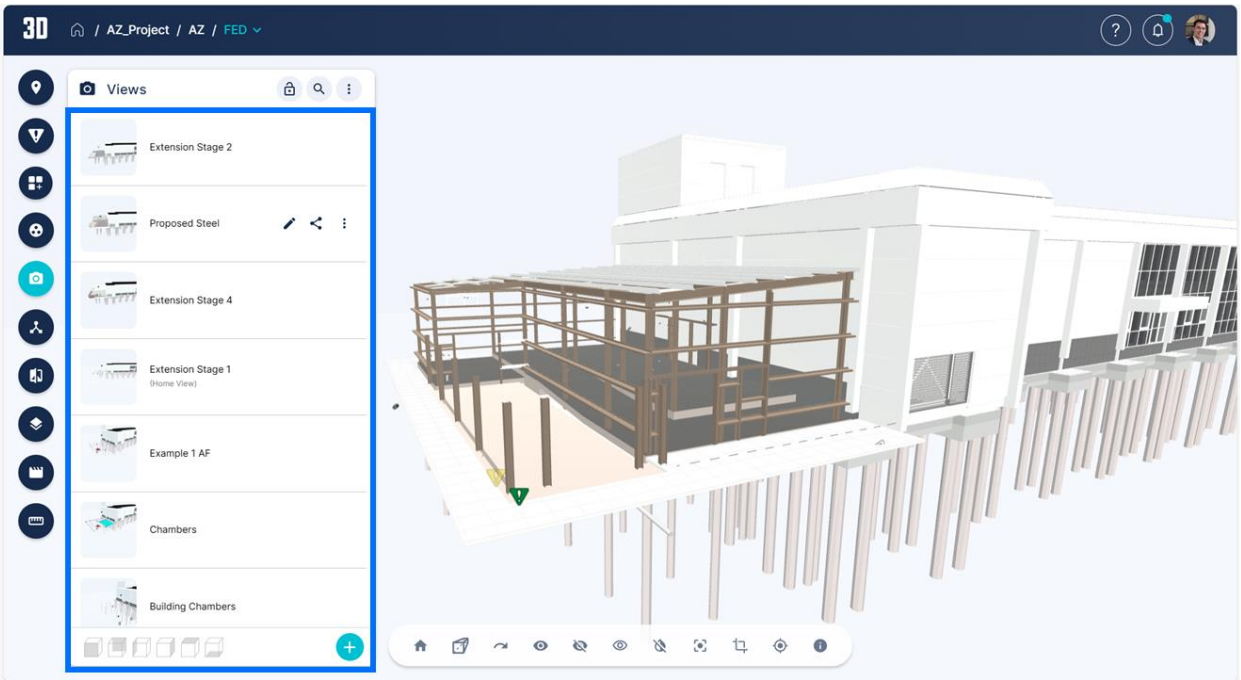


Figure 3. Identifying health and safety risks virtually within a BIM model.

2.1.2. On-site Zone management (Construction Phase)

During the construction phase, engineering controls play a role in mitigating some identified hazards by employing protective barriers between workers and potential risks. In order to create an integration between the traditional engineering controls and digital control measures, this trial focused on highlighting hazards using the BIM models, supplied by the client during the design phase. The hazards were marked as safety zones that needed to be monitored and controlled during construction using a network of sensing technologies. Zonal control should take into consideration the shape of the zone, ensuring sufficient clearance, the time the zonal control should be in place, and who/what should be able to operate within the zone, if any.

After assigning roles and access permits to personnel who should operate in the identified zone, the sensing system is deployed that monitor the locations of on-site personnel and machines in relation to the perimeter of the identified zone. In any case where personnel or machines enter a zone where they are not permitted, the system will automatically trigger an alert in real time for the unauthorised person/machine. The monitoring record will be used for lesson learnt to better understand and improve management strategies of future safety zones.

2.2. Technology Integration

This trial leverages digital control through the integration of two digital technologies, the modelling technology within the SafetiBase system from 3D Repo and the wearable sensors supplied by Plinx. The SafetiBase system is used to identify and capture hazards within the BIM model following the PAS 1192-6 standard. It is also used to highlight the safety zone that will be monitored and present their geometrical and temporal data. The sensing-based system is utilised for monitoring the identified zones in the physical construction site by tracking on-site personnel or equipment and alert the site operative in case of any unauthorised trespassing. An effective integration workflow of these two systems is required to ensure a seamless integration and data exchange between them. To achieve this integration, a bespoke API connection was developed by Plinx to receive data from SafetiBase. This data exchange enables the activation of alerts through helmet-mounted sensors, providing on-site personnel with real-time notifications in the face of potential hazards or unauthorised activities.

This bespoke API connection developed by Plinx allowed zone data including its XYZ coordinates, project reference point, and the start and end time of associated activities to be collected by the Plinx broker via 3D Repo's API. The broker then converts the XYZ coordinates to WGS8 (Lat/Lon) so that it can be used within the Plinx system. Plinx activates the zone at the start time and deactivates it at the end time. Meta information from the risk treatment ticket, such as zone type, purpose and supplementary information in the treatment notes is available within Plinx.

Non-authorised zone interaction data is immediately available to 3D Repo via Webhook. This includes location data and duration of incursions and is recorded on the model stored in 3D Repo as a SafetiBase risk with 4D start and end times. The location data (every 30s) history for all sensors is made available via API call, usually at the end of the day. The data is converted to XYZ by Plinx before export. With predefined 3D markers to represent the position of tracked sensors (shown in Figure 4) federated into the 3D model, a server-side backend script developed by 3D Repo processes the exported location data from Plinx to manipulate the location of these markers to show movement of tracked personnel/equipment as a 4D sequence animation; XYZ positions are stored as transformation groups for each sensor marker and bundled into a 3D view for each sequence frame of the 4D animation. All resulting sequence frames are concatenated together and stored as a custom 4D sequence on 3D Repo. Once within 3D Repo, the movement and zone interactions can be displayed on top of the 3D model with reference to the zone that was originally created in this environment. Figure 5 summarises this integration process.

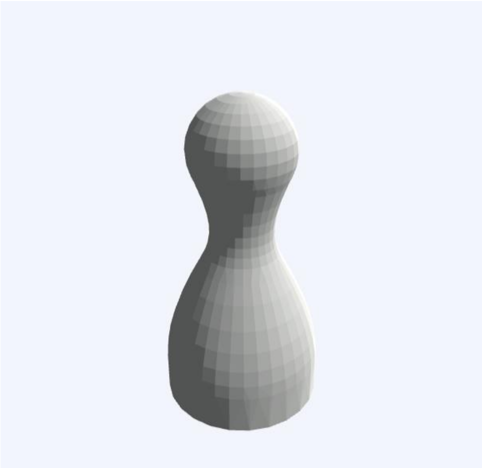


Figure 4. 3D marker representing location of tracked personnel.

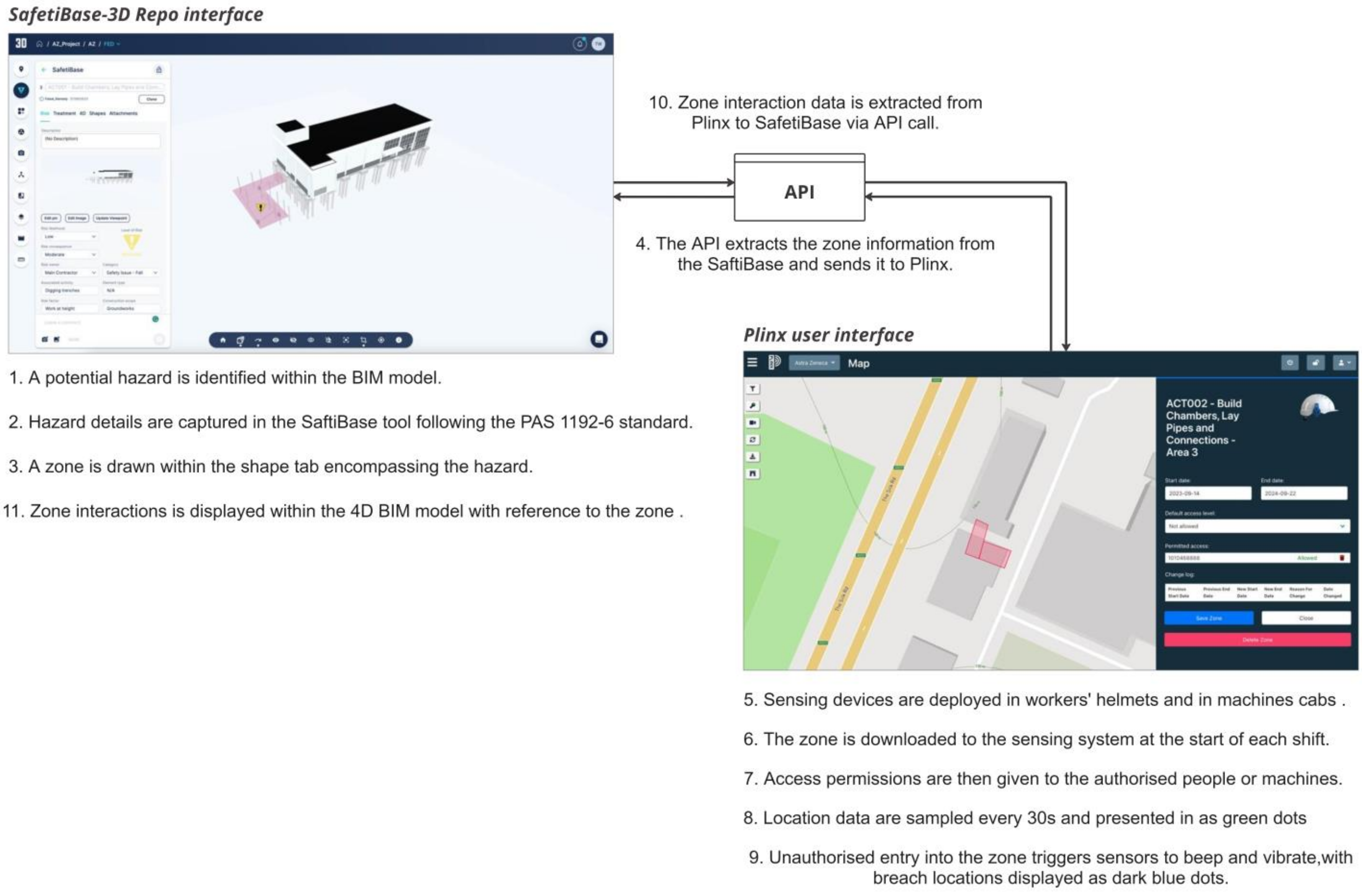
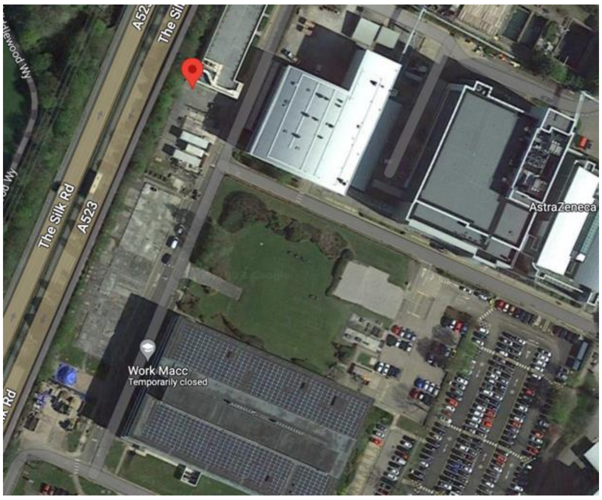


Figure 5. The steps of the integration workflow between the SafetiBase and Plinx platforms.

2.3. Trial Implementation

After ensuring the integration of both systems, an on-site trial is executed with the main goal of capturing authentic, real-world data from a dynamic construction site. This data, once obtained, will be systematically incorporated back into the 3D model environment, enhancing its contextual relevance. This iterative process not only solidifies the practical application of the integrated systems but also supports the overall effectiveness of the HEALTH AND SAFETY risk management framework. The on-stie trial was performed AstraZeneca's QAB extension project, Figure 6a. Initially, four construction activities associated with potential risks were identified, including footings excavation, drainage chamber installation, steel erection, and utilities connection into the road. However, due to the compact site and the multi-disciplinary nature of the chosen subcontractors, creating safety zones for roles and competencies for all these activities proved challenging. Therefore, we focused on the steel erection task, as it was completed by a specialist team, Figure 6b.



(a)

(b)

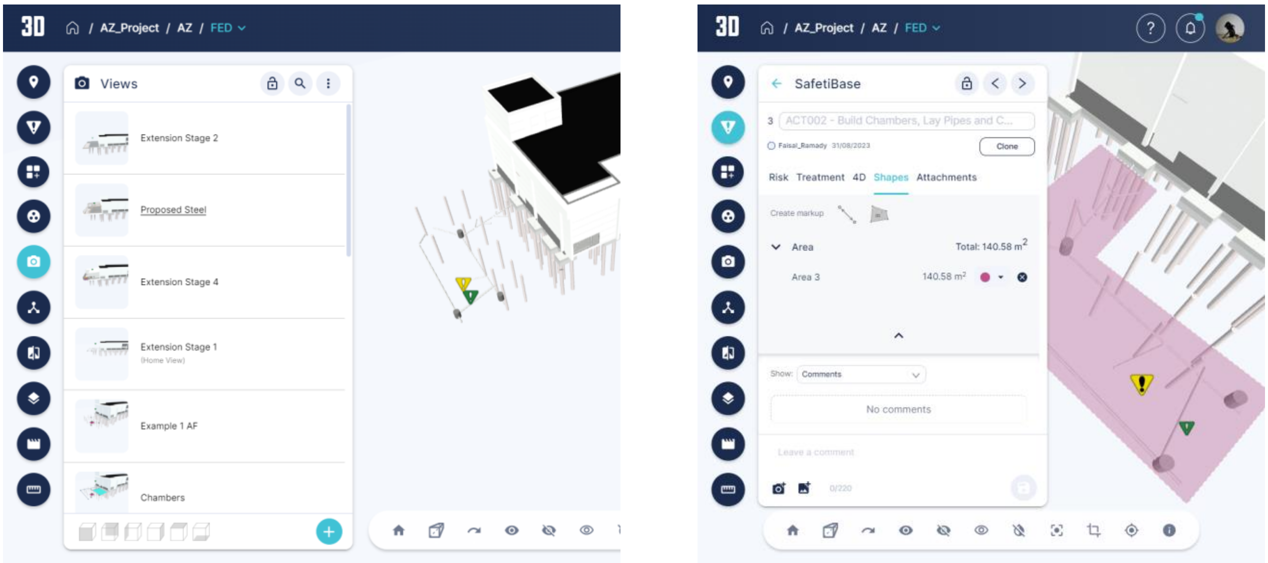
Figure 6. AstraZeneca's QAB extension project: (a) The location of the project in Macclesfield, and (b) the safety zone selected around the steel erecting work to be monitored and controlled.

2.3.1. Safety Zone Setup

Before setting up the safety zone on the BIM model of AstraZeneca's QAB extension, an initial trial model was created in the SafetiBase platform with the Dalkia team. This was done to provide the team with appropriate training on the SafetiBase risk management and shapes functionality, enabling them to properly manage risks and safety zones within the 3D Repo platform.

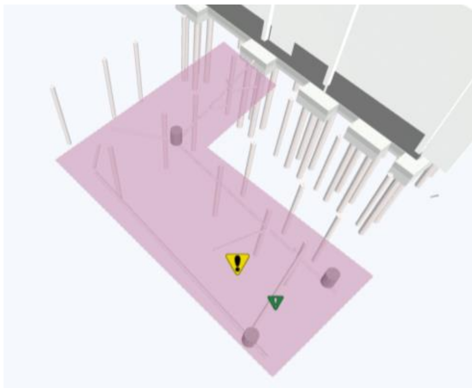
Once AstraZeneca's model was received, the model was prepared based on the findings from the trial model already setup, which included setup of the project base point, alignment of the federation, and inclusion of base plane to allow for safety zone setup across the site. Further work was undertaken to the model to reflect various construction sequence states of the project including setting up views with hidden elements to reflect main construction sequence and setting up plane and alignment of federation in Revit, Figure 7a.

The work package associated with the steel erection work was identified as a hazardous activity and safety zones were established around its locations with its hazard details in the BIM model. These areas of hazardous activity and safety zones are defined in SafetiBase using the shapes functionality as shown in Figure 7b. The shapes tool and create/update SafetiBase risk API allow for complex zones to be drawn via the visual polygon tool or an array of 3D points respectively, Figure 7c. The resulting zone is shown in Figure 7d; the zone and its data can then be extracted from SafetiBase via an API request and sent to the Plinx platform to be monitored on-site during construction.



(a) (b)


```
▼ shapes: [{_id: "64c9a2f0-5c4c-11ee-8856-4d013d4374ba",…}]
  ▼ 0: {_id: "64c9a2f0-5c4c-11ee-8856-4d013d4374ba",…}
    ▶ color: [0.776, 0.325, 0.549, 1]
      name: "Area 3"
    ▼ positions: [[392284039.5591035, 146000.0336670056, -375455340.1917413],…]
      ▶ 0: [392284039.5591035, 146000.0336670056, -375455340.1917413]
      ▶ 1: [392279626.1841035, 146000.03125, -375457478.4183038]
      ▶ 2: [392275462.4341035, 146000.03125, -375444696.6839288]
      ▶ 3: [392275462.4341035, 146000.03125, -375444696.6839288]
      ▶ 4: [392290160.004416, 146000.0390625, -375439112.0198663]
      ▶ 5: [392292640.0434785, 146000.03922537714, -375445668.0979913]
      ▶ 6: [392275462.4341035, 146000.03125, -375444696.6839288]
      ▶ 7: [392292640.0434785, 146000.03922537714, -375445668.0979913]
      ▶ 8: [392282391.9497285, 146000.03383602202, -375449185.5120538]
      ▶ 9: [392284039.5591035, 146000.0336670056, -375455340.1917413]
      ▶ 10: [392275462.4341035, 146000.03125, -375444696.6839288]
      ▶ 11: [392282391.9497285, 146000.03383602202, -375449185.5120538]
      type: 1
      value: 140575616
```

(c) (d)

Figure 7. Model setup within 3D Repo: (a) views reflecting construction stages, (b) shapes setup in SafetiBase to define safety zone, (c) JSON data from API request to 3D Repo to create safety zone, and (d) resulting safety zone.

Setup of 4D scheduling information for construction stages and timeframes associated with recorded SafetiBase risks allow for marked up hazardous activities and safety zones to dynamically change as the project progresses to ensure both the visual representations and data sent to the Plinx platform reflects the state of the site.

2.3.2. Sensing System Setup

The setup of the sensing system followed several key steps. Firstly, the sensor charging and allocation station, Figure 8a, was installed and activated within Dalkia's office. The TeamSense wearable sensors were connected to JSP construction helmets as illustrated in Figure 8b. Plinx RFID cards, Figure 8c, were issued to the workforce. The Plinx team delivered some basic training to Dalkia management describing how to setup the back end of the Plinx system including mapping operative roles and competencies against card ID's, in this case an excel spreadsheet was used, Figure 8d. Once the site was setup within Plinx Affect platform, operatives were able to scan their RFID card after their morning briefing to receive a sensor with personalised zone access.

To improve user adoption and analysis of sensor performance at the QAB extension site, the contractor agreed to wear the sensors for a week before the safety alerts were activated.

A further optional step was conducted during the trial to ensure accuracy of the placed zone where a survey rover, Figure 8e, was used to accurately plot a polygon on site relative to the mounting positions of the vertical steel beams. The survey rover outputted a GEOJSON file was uploaded directly to the Plinx platform to confirm alignment of the built asset with the Safety Zone plotted in 3D Repo.

(a)

(b)

(c)

(d) (e)

Figure 8. The sensing system setup: (a) sensor charging and allocation station, (b) wearable sensor connected to the safety helmet, (c) Plinx RFID card, (d) Spreadsheet of the roles and competencies of personnel mapped against their assigned IDs, and (e) a GNSS Rover

2.3.3. Safety Zones monitoring

Following the integration with 3D Repo, when a new zone was plotted in accordance with the construction sequence in the 3D environment, the zone was automatically converted to a 2D geo-referenced polygon in Plinx. Each of the site's zones were synchronised with the Powerbox positioned in the site offices via the internet. The corresponding zone data was then downloaded to each of the TeamSense wearable sensors in the box. Once zones were updated, the TeamSense sensors could allocated to operatives using their personal RFID card and attached to safety helmets. Because the ID of the card was linked with their personal access permission the wearer received personalised alerts and they would be alerted if they entered a zone where they were not permitted. During the trial, the designated zones were monitored, and location data was acquired at 30-second intervals from the wearable sensors. These data points were then visually represented on the platform as green dots, as illustrated in Figure 9. The monitoring system was specifically designed to trigger an alert when an unauthorised person entered the zone. To assess the system's responsiveness and reaction time, deliberate interactions were induced within specified areas of the monitored zone. Upon the entry of unauthorised individuals, their sensors would beep and vibrate, with the location of these breaches being visible on the platform as dark blue dots, as depicted in Figure 9.

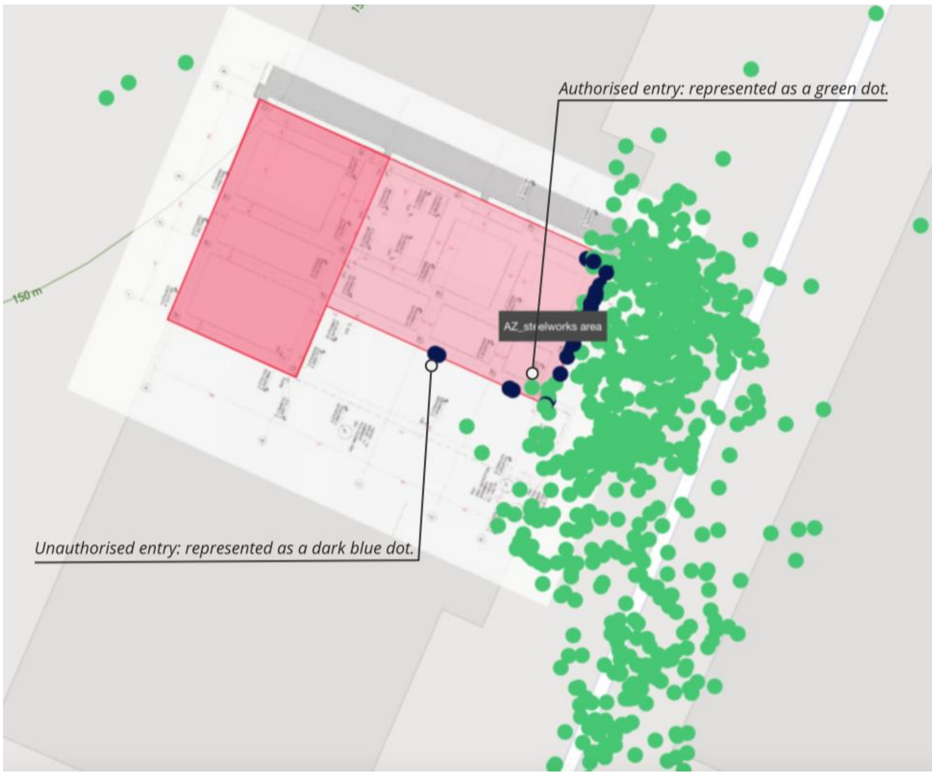
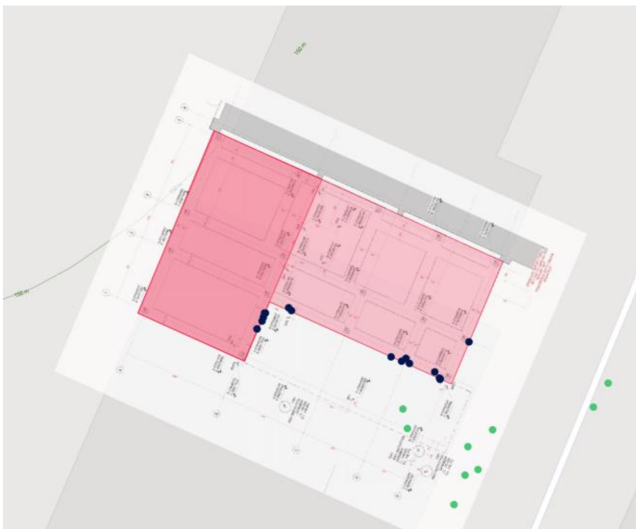
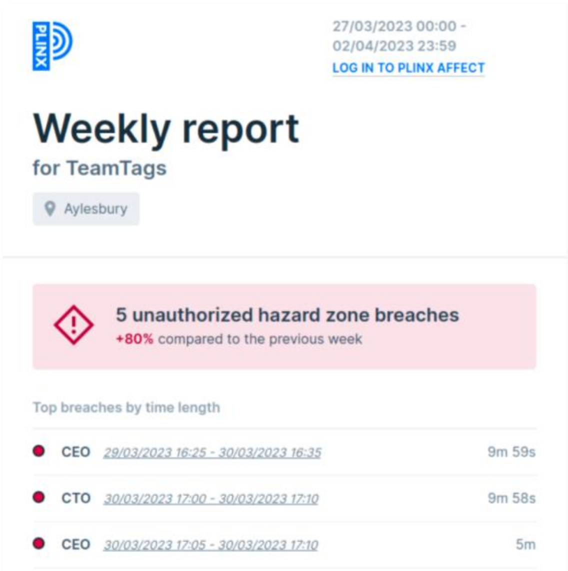


Figure 9. A screenshot from the Plinx platform highlighting the real time location data of on-site people relative the defined zone, with authorised entries to the zone presented as green dots, and unauthorised ones as dark blue dots.

All unauthorised incursions to the zone are recorded and presented in a weekly report indicating the number of breaches and the associated information of each breach (e.g., personnel ID and role, date and time, and the duration of presence in the zone), as illustrated in Figure 10.



(a)

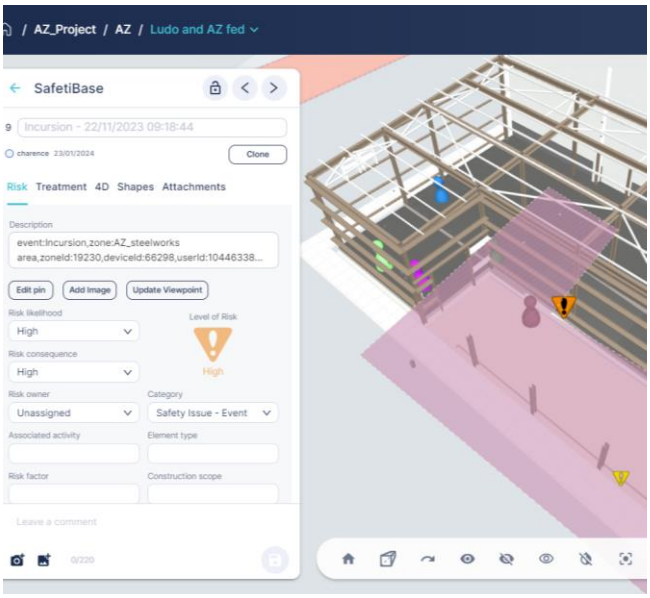


(b)

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

(c)



(d)

Figure 10. Recorded unauthorised incursions to the zone: (a) their locations on Plinx, (b) their information within the weekly report, and (c) data visualisations, and (d) imported SafetiBase risk events in 3D Repo of the steel work zone over the monitoring period.

The gathered monitoring data are used to enhance week-on-week management strategies of safety zones by playing it within the BIM model, as illustrated in Figure 11. More significantly, it plays a crucial role in providing insightful feedback to planners and designers, offering valuable insights into the efficacy 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.

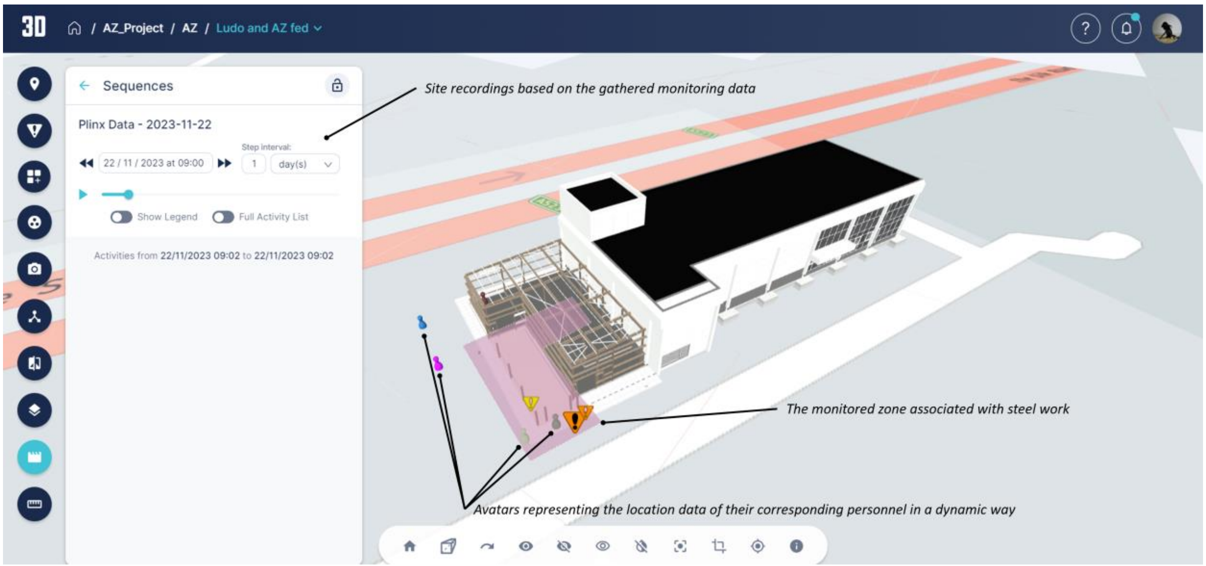


Figure 11. A screenshot from a video displaying the dynamic location data gathered during the zone monitoring within the BIM model.

3. Results

3.1. Trial Impact on Construction Safety

This trial has introduced the concept of digital control for enhancing workers' health and safety in construction sites through the successful integration of HEALTH AND SAFETY standards with digital technologies. These technologies involved the BIM technology that was used for virtual identification of hazard activities and safety zones in 4D models, and the monitoring-based sensing technology utilised for monitoring the identified zones on physical site.

A significant impact of this digital integration on safety lies in the realm of proactive hazard identification and management. Traditional safety measures often rely on reactive responses to incidents. However, the demonstrated digital control system, with its automated sensing and monitoring capabilities, enables the prediction and prevention of potential hazards before they occur. The real-time monitoring of safety zones, coupled with automated feedback loops, ensures that safety measures are not only effective but also responsive to dynamic construction site conditions. Moreover, the integration of a proactive alerting system adds an extra layer of protection within the digital control. Traditional safety measures often rely on manual processes for alerting, which can lead to late and/or missed detection of non-compliance. In contrast, the implemented system triggers immediate alerts when unauthorised individuals breach safety zones, enabling swift responses to potential risks. This level of responsiveness significantly reduces the likelihood of accidents and enhances overall situational awareness.

The digital control also extends to data visualisation within the model. This not only aids in better understanding the construction site's layout and potential hazards but also allows for a comprehensive analysis of safety data over time. The visual representation of safety zones and monitoring data within the BIM model facilitates informed decision-making, enabling stakeholders to identify trends, assess the impact of safety measures, and implement targeted improvements. The feedback loop, a key aspect of the digital control system, plays a pivotal role in refining safety protocols. Unlike traditional methods, where post-incident analysis is the norm, our system provides continuous, data-driven insights. Planners and designers receive feedback in a timely manner about the effectiveness of preventive measures, enabling swift adjustments and improvements. This dynamic feedback loop creates a proactive safety culture, with an emphasis on ongoing refinement and optimisation.

3.2. Challenges and limitations

Although this trial has demonstrated promising advancements in safety management through the integration of BIM technology and monitoring-based sensing, it is essential to acknowledge the challenges and limitations encountered during the implementation. These aspects provide valuable insights for refining the system and optimising its performance in scalable construction scenarios.

3.2.1. Technical Challenges

Integration complexity: The process of integrating and ensuring seamless data flow between SafetiBase and Plinx posed challenges, particularly during the initial exploratory phases where translation of X, Y, Z coordinate system to a map-based latitude/longitude coordinate system showed some potential for error and required manual manipulation and checking. Due to the size of the Quality Assured Building (QAB) extension we were not able to test large or complicated zones. Complete integration of Plinx and 3D Repo for defining safety zones was not feasible within the project timeframe and without a demonstratable MVP. Some zone configurations still required manual setup within the Plinx platform, meaning the site team needed to interface with multiple platforms to achieve the desired result. Given additional time, a customised SafetyZone interface could be developed within 3D Repo which would enable safety managers to authorise and restrict zone access to operatives, machines, or groups seamlessly as part of the SafetyZone planning workflow.

Need for more detail: The QAB model lacked a complete 4D sequence and omitted details about adjacent assets. During an online workshop with the client and contractor, we pinpointed four critical risk areas, but this proved time-consuming. Before work initiation, understanding the extension's construction methodology was challenging. It seemed that the sequence/methodology continued to evolve until work commencement due to insufficient details. Ideally, projects should adopt comprehensive 4D models encompassing temporary works elements for optimal planning and risk mitigation.

Lack of zonal standards: Another project challenge was related to acquiring and applying pre-approved treatment strategies that can be used as basis for establishing and marking up safety zones. This limitation has been recurrently observed across various contractors, attributable to the absence of a zonal control standard that can specify the attributes of a zone based on the activity parameters associated with it. For example, a safety zone for an excavation activity would vary in size and shape to a safety zone associated with steel welding activity. Plinx has already started some initiative to work with clients, contractors and designers to develop such standards.

Flexibility: Throughout the project, various external factors, including weather, equipment/material availability, and alterations in construction methodology, affected the project's schedule. Neither the Plinx nor 3D Repo systems possessed the flexibility to accommodate schedule adjustments based on these external influences. Presently, Plinx is exploring the impact of integrating project management software with BIM model and is collaborating with a leading planning system to develop a solution which would enable construction managers to swiftly modify task schedules and their related safety zones. It is crucial to synchronise Safety Zones with planned activities. Failure to do so may result in sensor alerts not aligning with actual locations, potentially causing undetected or erroneous zone entries. This misalignment could diminish the confidence of operatives in the system's accuracy and effectiveness.

Accuracy: The accuracy of the sensing system presented challenges at the QAB extension project. For example, during the survey Plinx tested the localisation performance on site, it was identified that the performance was poor due to erratic behaviour of the TeamSense and professional grade GNSS survey equipment. Surrounding metal clad buildings and electromagnetic interference are believed, but not proven, to have caused the location to be inaccurate. Plinx conducted tests elsewhere on site at Macclesfield and near similar buildings at different locations and are not able to replicate the issue. Achieving precise spatial alignment is key for effectively monitoring the designated zones. Another limitation of the current process is that the shape drawn in SafetiBase is a freeform polygon, whilst this offers ultimate flexibility to the user it will likely introduce discrepancies between physical segregation deployed on site and the digital zone. It is preferred that the system would apply standardised rules to the highlighted hazard aiding the designer to understand the impact on space and the site team when they are deploying physical barriers.

3.2.2. Operational Challenges

User Adaptation and Training: The successful implementation of our integrated system relied heavily on the proficiency of users in handling new technologies. The initial setup and configuration of exclusion zones in the BIM model and communication of the systems purpose and objective to the contractor and operatives required input from the HSE and Plinx. Effective user training, a clear demonstratable use case and ongoing support are crucial to overcoming this challenge, ensuring that all stakeholders can maximise the system's potential.

Privacy and Data Security: The deployment of sensing technologies raises concerns related to privacy and data security. Monitoring personnel through wearable sensors and capturing location data necessitates a careful balance between enhancing safety and respecting individual privacy rights. Striking this balance and implementing robust data security measures are critical for ethical and legal considerations, ensuring that the collected data is used responsibly and in compliance with privacy regulations.

3.2.3. Business Challenges

Cost Implications: The integration of advanced technologies, while promising, comes with associated costs. The acquisition, installation, and maintenance of BIM and sensing systems, along with ongoing training and support, may present financial challenges for smaller construction projects or organisations with limited resources. Striking a balance between the benefits gained and the financial investment required remains a crucial consideration for widespread adoption.

3.3. Lessons Learned and Future Recommendations

Implementing this trial provided valuable insights, leading to recommendations and lessons learned that will shape the future deployment of digital control, including the following:

1. Categorisation of Safety Zones: There is a clear demand for the categorisation of safety zones, distinguishing between areas designated for people and those for machines. To address this, 3D Repo will consider implementing features that facilitate such categorisation. This

enhancement aims to provide a clear understanding of the construction site environment, allowing for suitable safety measures for both personnel and machinery.

2. Automation of Zone Updating Workflow: To streamline workflow for project teams, automating the process of updating safety zones is crucial. This involves incorporating start and end dates of building activities according to the project programme within 3D Repo and sending this information through the API to Plinx. This enhancement ensures seamless communication with the Plinx platform, enabling automated activation and deactivation of zones based on project timelines. This automation not only improves efficiency but also reduces the risk of manual errors in zone management.

3. Utilisation of Shapes Functionality in 3D Repo: The shapes functionality in 3D Repo, designed for defining complex shapes for safety zones, presents an opportunity for further optimisation. Although not fully utilised in the current AstraZeneca model setup, additional training and refinement of the integration process are recommended. Ensuring that project teams are proficient in utilising the shapes functionality will lead to more accurate and contextually relevant definition of safety zones, aligning with project-specific safety requirements.

4. Conclusion

This innovative safety trial successfully demonstrated the practical application of integrating BIM and monitoring-based sensing technologies for identifying, monitoring, and managing hazard zones in construction sites. The trial's impact on construction safety is significant, introducing a paradigm shift from reactive to proactive hazard identification and management. By leveraging the capabilities of BIM for virtual hazard identification and the monitoring-based sensing technology for real-time monitoring, the integrated system enables for the prediction and prevention of potential hazards before they occur. This proactive approach, combined with a responsive alerting system, reduces the chance of accidents in construction sites. The digital control demonstrated in this trial extends to the visualisation of monitoring data within the BIM model, providing stakeholders with a comprehensive understanding of the construction site's layout and potential hazards. This data-driven visualisation not only enables informed decision-making but also supports continuous improvement through the dynamic feedback loop.

While the trial showcased promising proof of concept, it also highlighted challenges and limitations that needs to be addressed in future trials. The integration complexity between SafetiBase and Plinx, accuracy and calibration issues of the sensing system, user adaptation and training requirements, privacy and data security concerns, and cost implications are vital aspects that require further exploration and enhancement. Despite these challenges, the trial has provided valuable lessons and recommendations for the future deployment of the integrated system. Categorising safety zones, automating zone updating workflows, and optimising the utilisation of shapes functionality in 3D Repo are key areas identified for improvement in upcoming trials.