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An Intelligent BIM-Linked Augmented Reality Framework for Context-Aware Safety Orientation and Real-Time Hazard Detection in Saudi Arabian Giga-Projects

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Abstract
Saudi Arabia's giga-projects are large, geographically extensive and interdependent, posing a challenging space for occupational health and safety (OHS) management. Traditional uses of induction, periodic inspection and retrospective incident analysis were still essential but they did not continuously link planned work conditions with the different states of the site and the safety information it provided to its workers. Recent advances in building information modelling (BIM), augmented reality (AR), computer vision and artificial intelligence (AI) offered complementary capabilities, however, requiring BIM to be integrated with reliable data, the AR to be interpreted contextually, and AI to be performed with accountable human oversight. The conceptual study was proposed about an integrated BIM linked AR system for safety orientation and real-time hazard detection system for the large-scale construction project. It comprises a family of six closely-knit functions: (1) federated BIM and safety-information environment; (2) task- and location-specific AR orientation; (3) multimodal site perception (using computer vision and, if available, data from the Internet of Things (IoT)); (4) contextual hazard reasoning (relating perceived objects and activities with BIM geometry, work packages and safety rules); (5) risk-tiered alerting and human-led intervention; and (6) a feedback and assurance layer for learning, auditability and model updating. Theoretical underpinning of the framework was technology acceptance model, socio-technical systems thinking and systems theory. It's not only co-located, but sets of information interfaces, governance controls, decision logic and evaluation requirements to take the digital observations and transform them to defensible safety actions. The paper presents: technical performance, worker learning, operational response and organizational readiness, through propositions, implementation plan and validation protocol. The framework is not an empirical one – it is a conceptual design design that does not claim to be effective or to reduce accidents. It offers a testable framework for future pilot studies in Saudi Arabian giga-project environments.
Keywords: BIM; Safety, AR; Artificial Intelligence (AI); Hazard Detection.

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1. Introduction

The construction environment is temporary, dispersed and dynamically reconfigured, making construction safety management challenging. Temporary works, plant, materials, subcontractors and workers are interdependent and dynamic, moving around the site in accordance with the site conditions and the various schedules (Kaja & Goyal, 2023). A hazard can thus arise at the time, place and sequence of activities that are usually safe. Typical safety management systems are based on induction sessions, toolbox talks, permit-to-work, inspection and incident reporting. These controls are still critical but are often spread out between drawings, schedules, inspection records, contractor systems and the local communications. This can cause risk conditions to be missed until they change and may create challenges in providing appropriate training to appropriate personnel in appropriate locations (Chou et al., 2025).

Digital construction technologies may help to overcome this information gap (Adekunle et al., 2024) but they are not the same. That could include organising spatial and asset information in BIM, overlaying digital guidance on a worker's view of the physical environment in AR, and using AI-driven computer vision to identify an image or video to match selected objects, conditions and interactions in the physical environment. Recent reviews highlight the remarkable progress of AI-driven safety monitoring in the last few years, particularly in data quality, generalizability, interpretability, privacy, and embedding safety monitoring into the current workflows (Badhan & Samsami, 2025; Rabbi & Jeelani, 2024). AR research also suggests that its use is growing in the construction visualization, inspection, training, and safety areas, with usability, hardware, interoperability, and organizational barriers being identified as potential barriers (Calik et al., 2025).

The Saudi Arabian giga-projects were among the cases that were significant in these challenges (Filippi & Mazzetto, 2024). There can be large work fronts with many concurrent work fronts, extensive temporary logistics, large lifting operations, high-rise and infrastructure work, large multi-national work force or multiple combinations of these. The framework presented here is not necessarily applicable to any individual project, and the actual safety performance and technology deployment of a particular project will vary. Instead, these conditions inspire certain architecture that can tie together planned safety information, observed site conditions, and available worker guidance.

Previous works have focused on BIM-based safety checks, computer vision monitoring, AR-assisted construction, and digital monitoring of entry into hazardous zones (Tran et al., 2025). The various research streams do not necessarily define what the event means in the context of the BIM at the time of the incident, the translation of this information into a worker-facing instruction, the reporting of the incident to the appropriate level of authority within the site, and the recording of the incident as an audit record of safety (Li et al., 2022). For instance, an object detector can detect a person working near a crane, but if the person is near the crane doesn't mean the worker is in violation. The interpretation needs to be based on the workers role, equipment state, exclusion boundary, and active lift and site rules. More recent studies on entry to hazardous areas also highlighted the various types of equipment hazards, both static and dynamic, and the need for an integrated monitoring approach (Tran et al., 2025).

This study was aimed at addressing the following research questions:

(1) What are the possibilities of connecting BIM-based safety information with AR for providing task and location-specific worker orientation?

(2) How to understand the AI-based visual observations with respect to the BIM geometry and work activities and safety rules to find potential hazards?

(3) What were the organizational, human, and technical precautions needed for safety and accountability to make automated detection into automated intervention?

The purpose of the study was to produce a theory-based conceptual framework, delineate its functional layers and information flows, and set up propositions and a validation agenda for future field research.

This paper makes three contributions to the research. First, it puts forward a problem of integration as a problem of context and action, rather than a problem of technology-staking. Secondly, it adopts a human in the loop design approach, which involves using human interaction, data governance, and uncertainty handling and worker acceptance. Third, it proposes a multi-dimensional validation protocol that distinguishes between the accuracy of the model and outcomes of operation and safety.

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2. Literature Review

2.1 Digital transformation and construction safety data integration

Digital safety management is more than just digitizing paper forms. One of its core challenges is to link information produced at various points and by various actors in a manner that will ensure that risk controls remain relevant in light of the changes in work. BIM provides a structured representation of building and infrastructure components, spatial relationships, and project information. If the safety attributes are linked to objects, zones, work packages and schedules, the model can aid in planning and communicating risk controls. But BIM is not an accurate real-time representation of all site conditions. Materials may block access, equipment may be transferred, work sequences may vary from the baseline without warning, etc. Therefore, BIM should be used as a tool to serve as a context and be synchronized with observations and verified field changes (Aziz et al., 2024).

The advent of computer-vision and knowledge-based techniques provided a path toward associating visual information and structured safety knowledge. Fang et al. (2020) developed a computer vision-based construction safety assurance method and pointed out the potential of deep learning and technical and management barriers to application. (Zhang et al., 2022) also showed how computer vision and ontology can be integrated to create a knowledge graph for hazard identification. The significance of these studies is highlighted by the fact that they demonstrate the contribution of semantic relationships, as well as image classification, on hazard recognition. The BIM implication correlates a discovered entity with a spatial object, a state of operation, and a safety rule.

2.2 Safety planning and contextual hazard reasoning with BIM

BIM can provide spatial and temporal dimensions, which can help to separate a hazardous event from a harmless observation. Just because a worker is situated close to mobile plant, it does not automatically mean that they are unsafe. The system should be able to compare the estimated position of the worker to a current exclusion zone, the state of the machine, the active work package, and relevant control procedure. Likewise, the absence of a guardrail could be a mandatory component of an exposed edge, but be irrelevant where another engineered feature is accepted. This is a good example of the need for rule-based and context-sensitive reasoning, integrating BIM objects, work schedules, site observations and safety requirements that have been approved for the specific construction project (Martínez-Aires et al., 2018).

The importance of linking regulatory rules with the time-variant information of the BIM is further confirmed in recent research (Kim et al., 2024) in the field of automated safety risk assessment using such regulation-linked 4D BIM. The usefulness of such systems, however, hinges upon the use of model currency, the traceability of rules to the model, and a method for dealing with the discrepancy between model and field. Thus, the proposed framework can be seen as the use of BIM as a version-controlled safety information backbone but not as a suitable source for ground truth. Safety-critical objects or zones should have metadata that refers to their source, responsibility owner, verification date, and status.

2.3 AR for worker orientation and situated safety communication

AR could add digital information to the physical world via handheld devices, tablets or wearable displays. This capability can help to make abstract information, like an exclusion zone, evacuation route, overhead hazard or temporary access restriction visible in the right place for safety orientation. A worker may be given instructions, based on a specific task, location, role, and language, instead of just generic induction material. AR could also be used for brief interactive checks where workers can select hazards or demonstrate understanding prior to entering a high-risk work area (Lyu et al., 2025)

However, care must be taken in interpreting the evidence. A systematic review and meta-analysis of AR safety training showed a positive overall contribution of AR-based training, but no statistically significant difference between AR and traditional training was found in terms of knowledge acquisition in the specific comparison, while the authors indicated a lack of measurement of longer-term knowledge retention (Gong et al., 2024). This discovery reminds us not to infer that an immersive delivery will be a better learning experience. A more defensible design is one that incorporates AR to offer students situated practice and contextual reinforcement, along with competent teachers, supervised assessment, and built-in safety controls. A wider construction AR review from 2026 recognized cloud,

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hybrid and local architectures, and explored the integration of BIM, digital twins, IoT and UAVs, hardware, usability, interoperability and adoption challenges (Marinho et al., 2026).

2.4 AI and computer vision for hazard detection.

Computer vision software can automatically detect workers, PPE, vehicles, barriers and other entities on the site from images or video to select the monitoring tasks (Ahmed et al., 2024) . It can also be used to achieve event recognition, such as entering restricted areas or unsafe worker–equipment proximity. The technology was attractive for large projects because manual observation is not able to continuously monitor each and every work front. However, detection performance was found to be sensitive to the occlusion, camera placement, light, dust, motion blur, viewing angle, and training and deployment environment differences. Performance in a successful model cannot be guaranteed to be the same on a different model and/or later stages of the construction project. This progress has been summarized in recent reviews, with a call for a wider range of data modalities, as well as stronger deployment practices. By studying the AI applications related to text, visual and audio data, Rabbi and Jeelani (2024) identified opportunities and challenges in construction safety. Based on data analysis of 122 studies, Badhan and Samsami (2025) conclude that recognition and monitoring of PPE is a frequent application of deep learning and computer vision, noting data quality, generalizability, interpretability, privacy and workflow integration as prevalent challenges. To tackle the cost and labor of large-scale image annotation, Chen et al. (2025) show the practical applicability of SRL in PPE violation monitoring, using video-clip extraction. The results resulted in a design with confidence bounds, automated recognition, temporal consistency check, context rules and human check. A survey of deep learning and computer-vision applications in 2026 also showed PPE monitoring and hazard identification as major applications, and included a consideration of deployment conditions and implementation constraints (Mohy et al., 2026).

The output of AI should then be about potential risks, rather than just a conclusion of the misconduct or unsafe behaviours, along with some evidence and confidence. The system needed to be able to distinguish between detecting the presence of objects, determining the events, inferring risk and determining that the situation is not safe. This was essential for proper treatment of workers and not relying too heavily on faulty automation (Vivekananda Reddy Uppaluri, 2025).

2.5 BIM, AR, AI, and connected sensing integration

BIM, AR, and AI are complementary tools yet also pose integration challenges (Awe et al., 2025). BIM conveys the context of the project, computer vision can capture certain aspects of observed site conditions, AR can send certain information to the workers when appropriate and permissible, and IoT can send location, equipment, environmental, or physiological signals when appropriate and authorized. The data pipeline needs to reconcile coordinates, times, object identifiers, and models versions. It must also be able to resolve the situation when there are conflicting sources, such as a camera perceived the access route to be blocked, and the BIM model saw it as open. Their different contributions and main integration dependencies are summarized in Table 1.

The results of hazardous area entry monitoring research demonstrated that there are three categories of construction risk scenarios: static hazards, dynamic hazards, and multiple machine operations that overlap in the hazardous area. According to the review conducted by Tran et al. (2025), computer vision, the Internet of Things, and integrated solutions are three dominant technology groups, and the issues with dynamic site conditions are identified. The implication for the framework was that hazard detection had to be scenario specific and that a framework based on hazard detection using a single camera model could not be assumed to capture all relevant hazards.

2.6 Research gap

It was known from the literature that BIM can organise and structure safety information, AR can facilitate situated communication and AI can help automate aspects of visual monitoring (Asadi et al., 2019). Yet the gap that remains is architectural and organizational, how do these elements mesh together so that an observation generated by a machine can be a valid and important, worker-understandable, and auditable safety action? There are also existing technology-focused studies which offer building blocks, but the important issues to consider when designing an integrated system are synchronization, uncertainty, escalation, human accountability, privacy, and feedback. This study tackled that need by providing a six-function framework for large and distributed construction environments.

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Table 1. Complementary Roles & Dependencies

Technology	Contribution	Dependency/Limitation	Design Role
BIM	Structured spatial, object, schedule, and safety-control context	Model currency, semantic consistency, coordinate alignment	Provides the authoritative project and hazard context
AR	Situated, role- and location-specific safety communication	Device usability, registration accuracy, cognitive load, language access	Communicates relevant hazards, routes, and controls to workers
AI/computer vision	Automated recognition of selected site entities and events	Image quality, class imbalance, false alerts, domain shift	Generates uncertain observations for contextual assessment
IoT / telemetry	Additional information about equipment and changing site conditions	Sensor reliability, connectivity, calibration, data governance	Enriches situational awareness where justified
Human safety oversight	Interpretation, verification, intervention, and accountability	Training, authority, workload, clear escalation procedures	Retains safety-critical decisions with competent personnel

3. Theoretical Foundation

3.1 Technology Acceptance Model

The Technology Acceptance Model (TAM) was used to account for the use of technology in terms of perceived ease of use and usefulness (Davis, 1989). Within the developed framework, perceived usefulness is the perception of workers and safety professionals regarding the improvement of the understanding of the task, awareness of hazards and coordination of response when using BIM-linked AR and AI notifications. Perceived ease of use refers to the ease by which instructions are accessed and understood, without adding to the cognitive or operational load. The relevance of TAM was in the fact that a technically competent system can be unsuccessful if workers do not believe what it is providing, or they are unable to use the system in practice. Usability, language accessibility, device comfort, and alert relevance are taken into account as implementation conditions for this reason.

3.2 Socio-technical systems perspective

Safety performance is seen from a socio-technical approach, which takes into account interactions between people, technologies, tasks, organization and the broader work context. In this study, AI detection is not considered an autonomous safety decision-maker (Law et al., 2026) . It is to be utilized by authorized personnel and linked to established procedures, supervision, worker involvement, and corrective-action processes. A view also emerged here that there is a danger of loss of confidence in surveillance technologies when their aim, usage regulations and retention of data are not clear.

3.3 Systems Theory

Systems Theory gives a reason to look at the framework as being composed of a whole. The six functions share, and generate feedback loops: BIM provides context, AR provides guidance, perception systems provide observations from the site, reasoning logic evaluates potential hazards, intervention processes coordinate, and monitoring provides results for updating in the future (Adams et al., 2014) . Failure of a component can cascade through the system. For instance, a problem with an old BIM zone can lead to the generation of incorrect AR guidance and hazard classification. A system approach to validation, then, was a means of validating all the technologies together, rather than one by one.

3.4 Integrated theoretical logic

All three points of view complement each other. TAM explained individual acceptance, socio-technical thinking explained how technology should align with people and organizational practices, and Systems Theory explained the dependencies and feedback between technical and organizational aspects. They conclude that the factors of technical ability, user acceptance, organizational readiness, and reliable system integration are all required for successful implementation (Birken et al., 2017). The following propositions and evaluation dimensions are based on these theories.

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4. Developed BIM-Linked AR Safety Framework

4.1 Framework overview

A set of six interconnected functions was included in the developed framework. It has been built as a closed-loop safety information and intervention system, where safety-critical decisions are made by the human. The functions have been described in sequence for clarity, but data may be exchanged in operational mode in parallel and simultaneously. The information flow and interactions are depicted in figure 1 and the inputs, activities, outputs and safeguards for each function are summarized in table 2.

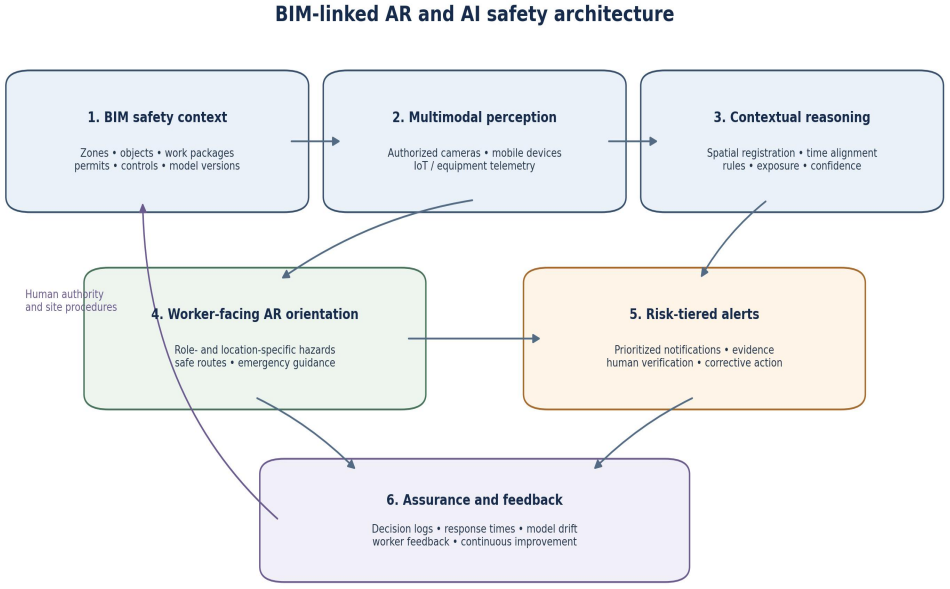

Figure 1. BIM-linked AR and AI architecture for context-aware safety orientation and hazard detection

4.2 Federated BIM and Safety-information environment

It was a federated BIM environment to establish connections between spatial geometry and object identifiers with construction zones, access routes, emergency exits, operating areas of equipment, temporary works, lifting zones, work packages and approved safety controls. If applicable, the model should be linked with the construction schedule and permits to work, and the risk context should reflect the current phase of construction. Every safety-critical data element should contain a responsible owner, a data source, a data version, a verification date and a status (Ma & Qi, 2026). To minimize reliance on a single software platform, it is important to use open exchange formats and documented interfaces to share data.

4.3 Function 2: Task- and location-specific AR orientation

The system accesses safety information at onboarding or prior to the task to meet the requirements of the worker, assigned activity and location. Only the boundaries, hazard markers, emergency routes, equipment interaction zones, PPE requirements and brief procedural prompts were shown on the AR interface. There should be Arabic and English as basic interface languages, and other languages as appropriate based on the workforce assessment process and not assumption. Use text to support visual symbols, audio prompts and short demonstrations. A knowledge check could be used to document the worker's appreciation of important hazards, but should not replace formal competency assessment or mandatory induction.

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4.4. Multimodal site perception is the fourth function

The perception layer fed data from the authorized fixed cameras, mobile devices and –where warranted – IoT (Internet of Things) sensors or equipment telemetry. The computer-vision models can identify workers, PPE, vehicles, barriers, openings, and certain activities. The sensor data can be used to give complementary location or equipment-state information. The system had to retain the timing and source metadata and to document uncertainty. The placement of cameras and selection of sensors should be based on risk and limit the unnecessary collection of worker identification.

4.5. The student can use hazard reasoning in context

Spatial registration, coordinate transformation, and time synchronization are used to identify the entities and map them to BIM objects and zones. A rule engine then determines if the observation violates an existing safety control. For instance, a person working within a crane exclusion zone could trigger a potential intrusion only if the crane excludes a specific zone, it is authorized or lifting, and the worker is not a legitimate person to work within the zone. The reasoning process should take into account, among other things, the thresholds for confidence, repeated observations, temporal persistence, and known exceptions. If data are not available or conflicting, the system should alert on the case to be reviewed, not assumed as correct.

This function is all about risk-tiered alerts and human-based intervention. In this function, the focus is on risk-tiered alerts and human-based intervention. Potential events are ranked on the basis of severity of the credible hazard, exposure, confidence of observation, and urgency of response. Low-confidence observation can result in observation being logged for review, moderate concern can result in a worker warning and escalation to the authorized safety team, and high-confidence observation can result in immediate worker warning and escalation to the authorized safety team. The goal of the alert is to convey location, condition, control, confidence, and action. Human personnel continued to be used to verify events and to launch operational measures. The system must not automatically approve work, cancel permits or substitute for emergency procedures.

4.6 Function 6: Feedback, assurance, and continuous improvement

The last function logs alerts, human actions, corrective actions, response times, model versions and associated inspection results. These records will enable the safety team to identify: areas of hazard repetition, areas of potential hazard, false-alert patterns, orientation gaps, etc. Changes that have been verified should be updated in the BIM environment and training content in a controlled manner. This provided a learning loop and maintained an audit trail of what the system has detected, what a human reviewer has determined, and what action has taken place as a result.

Table 2. Six-layer safety architecture

Function	inputs	Processing/activity	Outputs and safeguards
1. BIM safety context	Federated model, zones, work packages, permits, safety rules	Link objects and locations to current controls and responsibilities	Versioned safety context; named model ownership
2. AR orientation	Worker role, assigned task, location, approved controls	Retrieve and display relevant hazards, routes, and emergency guidance	Task-specific guidance; accessible language and interface
3. Multimodal perception	Authorized video, mobile imagery, selected sensors	Detect entities and candidate events; record confidence and timestamps	Evidence-linked observations; privacy and access controls
4. Contextual reasoning	Detections, BIM geometry, schedules, permits, rules	Register coordinates; align time; evaluate exposure and rule conflicts	Contextual risk candidates; uncertainty retained
5. Risk-tiered intervention	Risk candidates, severity, exposure, confidence	Prioritize; notify; require human review where safety-critical	Auditable alerts and verified corrective actions
6. Assurance and feedback	Alerts, decisions, actions, inspections, user feedback	Analyze recurring patterns, response times, drift, and usability	Continuous improvement; traceable governance records

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5. Research Propositions

The study is conceptual, so the propositions are theoretically derived expectations to be tested in the future.

- P1: Better content, timeliness, and semantics of BIM-based safety information will enhance the contextual relevance of digital safety guidance.
- P2. Task- and location-specific AR orientation will be positively correlated with workers' perceived knowledge of site hazards and emergency procedures.
- P3: Computer-vision based hazard detection will be supported by BIM based contextual spatial/operational context, allowing for greater contextual validity of hazard alerts selected when compared to image only detection.
- P4: Risk-tiered alerts with human verification will be positively related to timely and appropriate corrective-action responses.
- P5. Worker and safety-professional acceptance of BIM-linked AR system will be positively impacted by perceived usefulness and perceived ease of use.
- P6: Organizational support, digital competence, data governance, and interoperability will improve the link between technical capability and successful operational implementation.
- P7: Ongoing feedback and assurance will enhance the quality and timeliness of the safety information across the various stages of the project.

6. Methodology

6.1 Research design

This paper used a conceptual and design-oriented research approach. It combines the latest studies on BIM-supported safety planning, AR applications, AI-driven hazard identification, and digital surveillance to obtain a developed architecture (Gamage, 2025). There is no primary survey, field experiment or project deployment reported. It was therefore presented as a design framework that needed to be validated rather than an empirically tested intervention.

6.2 Pilot setting and sampling

A pilot could take place in one of the delineated work zones of a giga-project **in** Saudi Arabia or a similar-sized construction project. The pilot should start with a list of identified hazards (not all hazards) rather than try to search for all hazards. The participants may be relevant workers, supervisors, safety officers, BIM coordinators or project technology workers. Selection should be based on the tasks and languages used at the pilot site. Access, consent, data protection and safety approvals need to be obtained prior to data collection.

6.3 Data requirements and preparation

The pilot would need to have a current BIM model, zone and work package definitions, approved safety rules, schedule and permit information (if available), approved image and/or video data and a log of verified safety events. Guidelines for annotation should include an explanation and definition of each hazard class, inclusion/exclusion criteria, temporal boundaries, and evidence required to label an event. To minimize the leakage of information, training, validation and test datasets should be separated at the site level, work-zone level, or at the time-period level where possible. The test set should include various lighting conditions, weather, camera angles, PPE configurations, and construction phases.

6.4 Technical evaluation

For the computer vision component, use precision, recall, F1 score, mean average precision (mAP) by hazard class and not just the mean (Sarswat et al., 2024) . Since both false-positive and false-negative rates have operational consequences, they should be reported. Other parameters to be measured include inference latency, end-to-end alert latency, system uptime, and spatial localization error. The assessment of BIM synchronization should be done in terms

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of the consistency of the versions and in terms of the percentage of observations that are correctly mapped to the zone or object. AR should be evaluated in terms of registration accuracy, task completion time, interface usability, and the percentage of users who understand the instructions that are presented in the AR. The technical, operational, human, and governance indicators to be reported are organized in Table 3.

Table 3. Evaluation domains and indicators for a future field assessment

Evaluation domain	Suggested indicators	Interpretation/reporting requirement
Detection performance	Precision, recall, F1-score, mAP by hazard class	Report class-level results and confidence thresholds; avoid aggregate-only claims
Error and alert burden	False-positive rate, false-negative rate, alerts per worker-hour	Separate missed hazards from nuisance alerts; assess operational consequences
Contextual validity	Correct BIM-zone mapping, localization error, time-alignment error	Compare image-only detection with BIM-contextualized assessment
Response process	Time to acknowledge, time to verify, time to corrective action	Use verified event timestamps and describe escalation pathways
Worker learning	Immediate comprehension, delayed retention, route and control knowledge	Compare baseline orientation with AR-supported orientation using consistent instruments
Human factors	Perceived usefulness, ease of use, trust, cognitive workload, usability	Report by worker role and relevant language/device conditions
Governance and reliability	Data completeness, model drift, uptime, access events, retention compliance	Document auditability, cybersecurity, privacy, and model-version controls

To carry out human and organizational evaluation. To conduct human and organizational evaluation. The following are factors that should be considered during worker evaluation: hazard recognition, knowledge acquisition (immediate knowledge), delayed knowledge retention, emergency route comprehension, perceived usefulness, perceived ease of use, trust, and cognitive workload. If conventional orientation is instituted, as well as conventional orientation with AR then a comparison between these two can be considered. When a controlled or quasi-experimental design is the appropriate method, prior experience, language proficiency, job role and task type should be controlled. The metrics to be used for operational evaluation should include alert acknowledgement, time to verification, time to corrective action, and percentage of alerts that lead to verified actions. It is not enough to use accident frequency as a short-term endpoint as the number of accidents is relatively small and reporting can vary after introducing the system.

6.5 Validation and reporting

Validation should take place in phases: laboratory or model testing offline; shadow-mode deployment where alerts are captured but not used to direct deployment; supervised pilot deployment; and safe and well-governed expansion following. Shadow mode was important because it enabled the evaluation of false alerts, missed events, and synchronization issues without the risk of adding untested automated instructions into the live work environment. Results should include confidence intervals (if applicable), performance at the class level, performance at the sub-group level, and failure cases. An independent review of a subset of alerts may provide some measure of confidence in the reliability of human verification. The sequence can be summarized as shown in Figure 2**.**

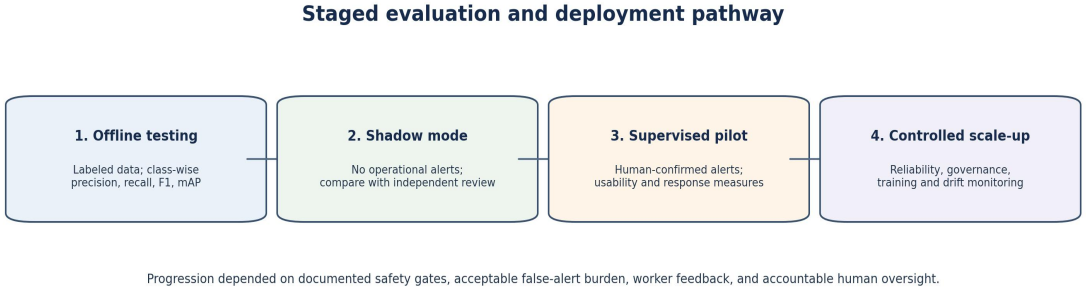

Figure 2. Staged evaluation pathway with safety and governance gates

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6.6 Ethics, privacy, and cyber-security

There is a need for clear governance of video monitoring and worker location data. The purpose of monitoring, categories of data collected, who can access the data, how long data will be kept and how errors can be challenged should be communicated to workers. Users must have access permissions based on their role, data must be encrypted when in transit and at rest, and data must be retained for a documented operational or legal purpose. Technological capability should not be reason enough to introduce facial recognition or identity inference. The pilot should be based on data minimization and privacy by design and meets the applicable Saudi legal and project requirements.

7. Phases

7.1 Phase 1: Readiness and use-case selection

The best approach to the project is to start with a collective readiness assessment of the owner, main contractor, safety leadership, BIM team, IT/cybersecurity staff and worker representatives. The team should choose a few use cases with the highest risk, number of exposures, ease of detection, and availability of effective controls. There should be a baseline established prior to implementing technology.

7.2 Phase 2: BIM & data governance

The project should be tasked with defining the authoritative BIM model, the coordinate reference system, the object identifiers, the responsibility for updating the model, and the responsibility for ownership of the safety-rule. Particular interfaces with scheduling, permits, equipment telemetry and safety management systems should be documented. A discrepancy-resolution procedure should be established to determine who would be responsible for verifying and updating a zone or safety attribute when the digital model and the field conditions are different.

7.3 Phase 3: AR & AI configuration

The AR interface should be evaluated with the representative workers in representative lighting, noise, heat and PPE conditions. When choosing devices, comfort, battery life, screen visibility, compatibility with necessary protective equipment, and the need for hands-free interaction should be taken into account. Care must be taken in training and testing AI models with representative project data and in not deploying them outside the hazard classes for which the results are acceptable.

7.4 Phase 4: Shadow mode and supervised pilot

In the shadow mode, the system should create records to compare with observations from outside agencies. The project team should look at hazards that were not detected or reported and how workers find the system confusing or problematic. Only after the agreed acceptance criteria are met should alerts be enabled for a limited supervised pilot. For any failure that could affect safety, pause, investigate, and take action.

7.5 Scale-up & lifecycle assurance

Expansion must be based upon technical reliability, user acceptance, manageable alert burden and clear accountability. Reassessment should be done if a camera is moved, if new equipment is used, or if cameras are replaced, if site layouts are changed, or if procedures are changed. Periodic audits should ensure that the system continues to be a supplementary control in the project's OHS management system and not replace necessary inspections, permits, training or supervision. Governance arrangements should also be connected with the risk-based planning, operational control, performance evaluation and continual-improvement logic of ISO 45001:2018 (International Organization for Standardization, 2018), which is the international standard for occupational health and safety.

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8. Discussion

8.1 From technology integration to context-aware intervention

The main leap forward was to outline the integration as a transformation from data to safe action. BIM, AR and AI are not value creators just by sharing a platform. The value of their combination was contingent on the ability to interpret an observation against the current work context, to communicate relevant instructions, and to tie the actions to the responsible site procedures. It is a focus that addresses the challenges in existing construction computer vision studies, such as data collection, accuracy, and managerial integration (Fang et al., 2020; Badhan & Samsami, 2025).

8.2 Consequences of safety orientation.

The approach adopted the framework of orientation as a continuous process and not just an induction process. AR could show hazards and controls in context, but there is no proof that AR is always better than traditional training. The work by Gong et al. (2024) resulted in a positive impact on the safety training process and the authors concluded that knowledge acquisition was not significantly different than the traditional method when comparing the two, and that there is limited evidence of retention. Therefore, AR should complement, not supplant, effective instruction and should be measured by meaningful learning and behaviour-based outcomes.

8.4 Concluding remarks

The framework separates detection and risk interpretation and confirmation. This distinction was important as an AI model can accurately identify a missing part of PPE or worker or vehicle, but not accurately identify the importance for safety. BIM linked reasoning can support the context only if the model and operational data are up-to-date. The work presented in Chen et al. (2025) shows ways to cut down the workload of annotating data for PPE monitoring, whereas the work presented in Tran et al. (2025) illustrates the various scenarios of hazardous areas in which PPE monitoring systems need to operate. The advances are for specific uses and not blanket statements of site surveillance.

8.4 Theoretical implications

The framework is an extension of TAM which places usefulness and ease of use in an environment of high-risk and time pressure in the workplace. It also uses a socio-technical approach, which considers worker participation, supervision, organizational practices, and governance an integral component of a system. Finally, the feedback architecture was based on the Systems Theory, which was that the accuracy of the entire system relied on the relationships between its components, rather than on the accuracy of any single model. Both views contribute to explaining why successful implementation is more about organizational design than technical choice.

8.5 Managerial implications

The framework proposed that BIM execution requirements should comprise of safety information, data ownership, rules for model updates and expectations for interoperability for project owners. Contractors need to delineate what types of hazards AI systems can be tasked with observing, and make sure the alerts are incorporated into response protocols. The responsibility of safety personnel to confirm alerts and prioritize interventions should be maintained. The relationships between users and the technology providers should be transparent with regard to the limitations of the model, the thresholds of confidence, the provision of information regarding the provenance of the data, and failure modes. It is important to involve worker representatives in decisions concerning interface design, language options and monitoring governance.

8.6 Contextual implications for Saudi projects

Scale, coordination among contractors, multilingual communication, and robustness to the environment are important design considerations in the context of the Saudi giga-projects. The framework thus called for multilingual and multimodal guidance, availability of key safety information offline, comprehensive equipment selection and staged

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deployment. These are the design needs to be evaluated application by application – they are not requirements for all giga-projects.

9. Limitations and Future Research

There were a number of limitations to this study. First, it's conceptual, and lacks empirical evidence that the developed framework increases hazard detection, training outcomes, or accident rates. Second, it's not prescriptive on software stack, camera setup, or AI architecture since they vary with project conditions and procurement requirements. Finally, the framework highlights specific visual and spatial risks; other data sources and professional judgment will be needed for risks such as fatigue, health, behavioral, structural instability and complex procedural violations. Fourth, for the framework to be effective, it had to be built on quality data, currency of BIM, BIM connectivity, acceptance by the workers, and a capacity of the organization to respond.

Future research should include pilot deployments to compare the effectiveness of orientation alone to orientation based on AR elements supported by BIM, measure delayed knowledge retention, and evaluate the ability of contextual reasoning to decrease the number of false alerts compared to image detection. Future research should explore the areas of explainable AI, uncertainty calibration, privacy-preserving analytics, digital-twin synchronization, and work permits and equipment telemetry integration. Long term evaluations are required to assess the effectiveness of the system on leading indicators including verified hazard closure, response time, etc., and near-miss learning. Further research is needed to explore benefit and error rates by worker role, language group, site zone and environment.

10. Conclusion

This study has evolved a conceptual AR-based framework to support the context-aware safety orientation and real-time hazard detection in Saudi Arabian giga-projects based on BIM. The architecture integrated a federated BIM safety environment, AR guidance that was task- and location-specific, multimodal site perception, contextual hazard reasoning, risk-tiered, human-led intervention, and a feedback and assurance process. Its central theme is the incorporation of digital safety technologies through the lens of the quality of interpretation and intervention, not as stand-alone tools.

The framework provides a structured design logic to connect planned safety controls, site conditions and worker facing information. It also clarifies that the detection of AI is not an automatic determination of violations, but an uncertain observation that requires human oversight, privacy, cyber security and data governance and acceptance by the workforce. Developed propositions along with validation techniques serve as a foundation for further empirical studies. Until validated, the framework is a conceptual design to be tested for safety and should not be considered a safety intervention.

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