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Transforming Occupational Health and Safety under Saudi Vision 2030: A Strategic Framework for Predictive, Digital and Resilient Workplaces

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Abstract- Saudi Vision 2030 is reshaping the Kingdom's economy, infrastructure, labour market, and institutional capabilities. Rapid expansion in construction, industry, logistics, tourism, advanced manufacturing, and large-scale infrastructure generates a parallel requirement for occupational health and safety systems capable of moving beyond compliance-led and injury-reactive approaches. This paper develops the Saudi Vision 2030 Occupational Safety Transformation Framework (SV2030-OSTF), an applied conceptual framework for progressing toward predictive, digitally enabled, worker-centred, and resilient workplaces. The framework was developed through a structured narrative synthesis of official Saudi policy sources, International Labour Organization instruments, and peer-reviewed OSH literature, with particular attention to Saudi construction and high-hazard work. Seven mutually reinforcing dimensions are proposed: (1) governance and assurance; (2) predictive risk intelligence; (3) occupational health and exposure prevention; (4) human capability, leadership, and worker voice; (5) digital safety and connected worksites; (6) prevention through design and lifecycle safety; and (7) resilience, learning, and operational readiness. A maturity model, an indicator architecture, a technology-selection gate, a five-layer safety intelligence reference architecture, and a phased 2026–2030 implementation roadmap are also presented. The framework deliberately treats technology as an enabler rather than a substitute for management commitment, competent supervision, worker participation, and effective risk controls. Its principal contribution is to connect national transformation objectives with an operational OSH architecture that can be piloted at sector, organisation, and project levels. The framework is conceptual and requires empirical validation before use in benchmarking or regulatory decision-making.

Index Terms- Computer vision; Digital safety; Occupational safety and health; Predictive safety; Saudi Vision 2030

I. INTRODUCTION

Saudi Arabia's Vision 2030 is a whole-of-economy transformation programme built around a vibrant society, a thriving economy, and an ambitious nation. Within the National Transformation Program, occupational safety and health is explicitly linked to labour-market attractiveness, workforce stability, and productivity, while the National Strategic Program for Occupational Safety and Health identifies regulation, awareness, capability building, inspection, and injury reporting as core pillars of improvement (Saudi Vision 2030, 2026a, 2026b). The establishment of the National Council for Occupational Safety and Health in 2022 further formalised national-level governance of the OSH ecosystem (NCOSH, 2026a).

The scale and speed of this transformation create a distinctive safety challenge. Large infrastructure programmes, complex supply chains, multinational workforces, intensified logistics, simultaneous operations, new technologies, and extreme climatic conditions can generate risk combinations that traditional lagging indicators are not designed to capture. At the same time, Vision 2030 presents an opportunity to design safety into new industries and assets from the outset, rather than retrofitting controls onto systems that have already matured.

Saudi-specific construction studies have repeatedly identified management commitment, supervision, risk appraisal, training, communication, worker involvement, and safety climate as important determinants of safety performance (Makki & Mosly, 2020, 2021; Mosly & Makki, 2020). More recent research points to growing practitioner interest in artificial intelligence, the Internet of Things, building information modelling, drones, and wearables, while emphasising that human and organisational factors remain fundamental (Ahmad et al., 2026; Mosly, 2026). A survey of 567 Saudi construction professionals found that smart safety vests and helmets attract the highest recognition, whereas advanced monitoring systems — including fatigue and environmental sensors — remain underused; adoption clustered around three factors: safety and operational effectiveness, worker acceptance and support structures, and technical and adoption barriers (Mosly, 2026).

Internationally, safety science has moved progressively from reactive injury counting toward leading indicators, resilience engineering, proactive control verification, safety climate, and Prevention through Design (Hallowell et al., 2013; Hinze et al., 2013; Hollnagel, 2018; Jin et al., 2022). In parallel, the construction research community has begun to operationalise Industry 4.0 technologies for safety: data analytics and artificial intelligence, robotics and automation, building information management, sensors and wearables, digital twin, and industrial connectivity are now treated as an interconnected portfolio rather than isolated tools (Turner et al., 2020). A recent systematic review of Industry 4.0 adoption for workplace safety found IoT to be the most widely implemented solution, followed by augmented reality, virtual reality, cyber-physical systems, digital twins, and blockchain (Melesse et al., 2026).

This paper therefore proposes the Saudi Vision 2030 Occupational Safety Transformation Framework (SV2030-OSTF). It is offered as a practical research framework, not as a claim that current Saudi OSH arrangements are inadequate. The framework organises evidence-based improvement opportunities into seven dimensions and translates them into maturity levels, indicators, a technology architecture, and a staged roadmap suitable for future piloting.

A. Research aim and questions

The aim of this study is to develop an evidence-informed conceptual framework that connects Saudi Vision 2030 transformation priorities with a proactive, health-inclusive, and technologically enabled OSH operating model.

- RQ1. Which OSH capability domains are most relevant to the rapidly transforming Saudi work environment?
- RQ2. How can reactive safety management be complemented by predictive, exposure-based, design-led, and resilience-oriented approaches?
- RQ3. How can these domains be translated into measurable organisational and project-level actions between 2026 and 2030?
- RQ4. Which emerging digital technologies have demonstrated value for construction and high-hazard safety, and under what governance conditions should they be adopted?

B. Contribution of the paper

The paper makes five contributions. First, it integrates national policy direction with contemporary safety science in a single Saudi-oriented model. Second, it broadens the focus from accident prevention to occupational health, cumulative exposure, and worker wellbeing. Third, it provides practical maturity and measurement architecture rather than a high-level vision statement alone. Fourth, it positions digital technologies within a socio-technical governance system encompassing privacy, competence, human oversight, and critical-control verification. Fifth, it supplies a technology-selection gate and a layered reference architecture so that digital investment is tied to defined hazard-control problems rather than to technology fashion.

C. How to read this paper

Sections 2 and 3 set out the Saudi policy context and the framework-development method. Section 4 synthesises the evidence base across eleven themes. Section 5 presents the seven-dimension framework and its socio-technical logic. Section 6 converts the framework into matrices, a maturity model, an indicator architecture, a technology gate, and a reference architecture. Section 7 presents the 2026–2030 roadmap; Section 8 applies the framework to five high-risk Saudi work environments; Sections 9–12 present the discussion, limitations, future research agenda, and conclusions, respectively.

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II. SAUDI VISION 2030 AND THE EMERGING OSH CONTEXT

Vision 2030's economic diversification agenda is associated with growth across infrastructure, industry, logistics, tourism, energy, technology, and services. These sectors carry different hazard profiles but share several system-level characteristics: extensive contractor ecosystems, accelerated delivery programmes, workforce mobility, digitalisation, shifting work interfaces, and pressure for high operational availability. An OSH model suited to this environment must therefore function across organisational boundaries and throughout the asset lifecycle.

The National Transformation Program identifies a National Strategic Program for Occupational Safety and Health and describes OSH regulation, awareness, capability development, inspection, and workplace-injury reporting as major components of labour-market improvement (Saudi Vision 2030, 2026b). NCOSH states that its role includes national governance, stakeholder coordination, oversight of the National OSH Policy, and the development of monitoring, evaluation, and accident-reporting arrangements (NCOSH, 2026b). Together with the Ministry of Human Resources and Social Development's guidance on occupational safety and health hazards, these developments provide an institutional foundation on which more data-driven and preventive approaches can be built (2022).

Saudi Arabia ratified ILO Convention No. 187, the Promotional Framework for Occupational Safety and Health Convention, in June 2024. The Convention emphasises continual improvement through a national policy, national system, and national programme for OSH. As of September 2026, ILO NORMLEX lists Convention No. 187 as in force for Saudi Arabia and Convention No. 155 as not ratified (ILO, 2024, 2026). This paper does not take a position on future ratification decisions; instead, it uses the general principles of continuous improvement, national coordination, and prevention as reference points for framework design.

Climate is another strategic variable. Outdoor work in Saudi Arabia can involve prolonged heat exposure, and contemporary Saudi construction research identifies extreme heat and adverse weather among prominent safety concerns (Mahmoud et al., 2026). A future-oriented OSH model therefore needs to integrate climate adaptation, exposure monitoring, hydration and rest controls, work–rest scheduling, and early warning, rather than treating heat solely as a seasonal compliance item.

A further contextual factor is the fragmentation of the Saudi construction delivery environment. Research on Saudi public-sector construction identifies high levels of fragmentation, a low-skilled, multilingual and multi-ethnic workforce, and inefficient use of BIM technologies as recurring challenges, with 18 factors influencing health and safety outcomes and better enforcement of regulations and laws identified as the key driver of improvement (Balgheeth, 2016). Any digital or predictive model must therefore be designed for communication across language and contracting boundaries, not only for data capture.

A. Transformation drivers and OSH implications

Figure 1 maps the principal transformation drivers onto the OSH capability shifts they demand.

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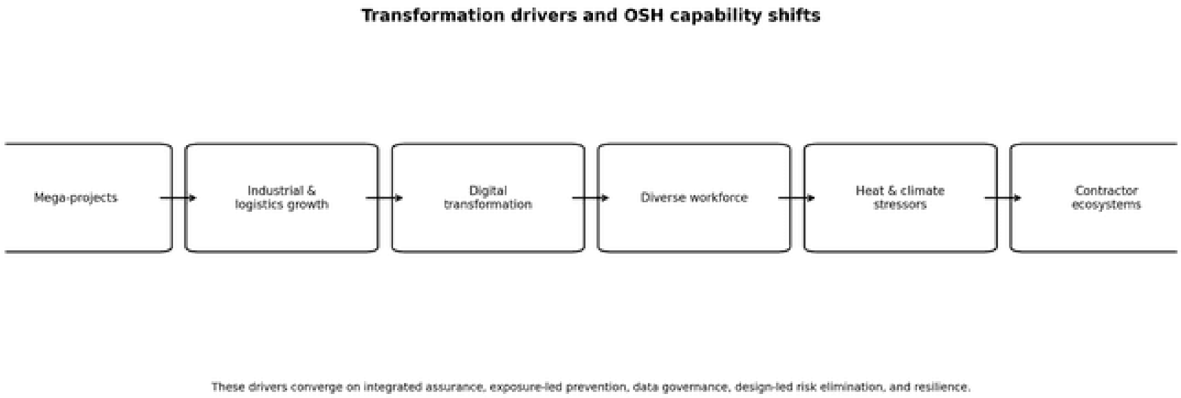

Figure 1. Transformation drivers and the corresponding OSH capability shifts.

TABLE I. TRANSFORMATION DRIVERS AND OSH IMPLICATIONS

Transformation driver	OSH implication	Required capability shift
Mega-projects and accelerated delivery	High interface density, contractor layering, schedule pressure	Integrated assurance, SIMOPS intelligence, critical-control verification
Industrial and logistics expansion	Energy isolation, lifting, traffic, machinery and process hazards	Lifecycle risk management and predictive control monitoring
Digital transformation	More sensors, automation, AI and data-rich operations	Data governance, human oversight and interoperable safety analytics
Diverse workforce	Language, competence and communication variability	Role-based competency, multilingual learning and worker voice
Extreme heat and climate stressors	Heat strain, fatigue and reduced cognitive/physical capacity	Exposure-based prevention, real-time monitoring and climate adaptation
Complex contractor ecosystems	Variable standards and fragmented accountability	Common assurance model, contractor maturity and transparent performance data

III. METHODOLOGY

This study uses an applied conceptual-framework methodology supported by a structured narrative review. It reports no primary human-subject data and claims neither psychometric nor causal validation. The objective is framework development: to synthesise policy direction and safety-science evidence into an operational model that can subsequently be tested.

The evidence synthesis proceeded in six stages. Stage 1 established the Saudi policy anchor using official Vision 2030, National Transformation Program, NCOSH, Ministry of Human Resources and Social Development, and ILO sources. Stage 2 reviewed peer-reviewed literature on Saudi construction safety climate, safety leadership, leading indicators, occupational exposure, resilience engineering, and Prevention through Design. Stage 3 reviewed the digital and Industry 4.0 evidence base, covering IoT, wearables, computer vision, machine learning, digital twins, extended reality, exoskeletons, blockchain, and connectivity architectures. Stage 4 applied thematic grouping to identify recurring capability domains and areas where emerging risks require additional emphasis. Stage 5 translated these domains into an applied maturity model, indicator architecture, and technology-selection gate. Stage 6 constructed the implementation roadmap and the reference safety-intelligence architecture.

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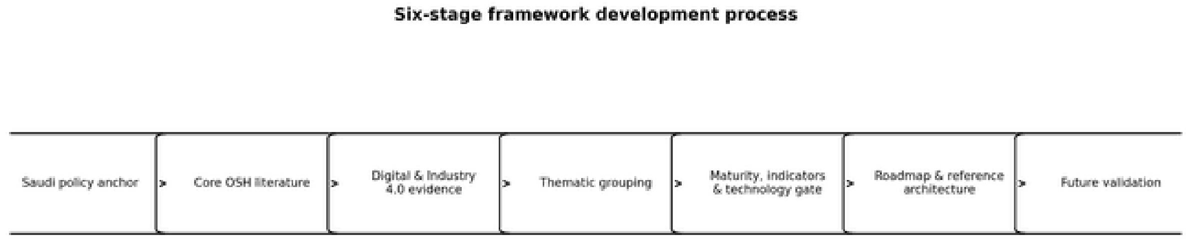

Figure 2. Six-stage framework development process and planned validation pathway.

Sources were prioritised when they were (a) official national or international policy documents, (b) peer-reviewed research directly related to Saudi OSH or construction, or (c) highly relevant safety-science or safety-technology literature supporting leading indicators, resilience, digital safety, or design-led prevention. Because the purpose was conceptual synthesis rather than exhaustive effect estimation, the review should not be interpreted as a systematic review with comprehensive database coverage or meta-analysis.

Framework dimensions were retained when they met three criteria: strategic relevance to the Saudi transformation context, support in established or emerging OSH literature, and practical measurability at organisation or project level. Overlapping concepts were consolidated to avoid a framework dominated by technology or compliance alone.

Technology components were included in the framework only when they satisfied two additional conditions: a documented safety application in peer-reviewed construction research, and an identifiable governance requirement (data protection, accuracy validation, or human response). This prevented the framework from becoming a technology catalogue.

A. Ethics, funding and conflict of interest

No new human participants were recruited and no new personal data were collected for this conceptual framework paper. Aggregated, de-identified results from the author's related practitioner exposure-management survey (N = 65) are used only as secondary contextual evidence in Sections 4.3 and 6.5; they are not used to derive framework weights, validate the SV2030-OSTF, or estimate causal effects. The originating survey methodology and ethics documentation should be retained with the companion study record and supplied to the journal if requested. The anonymised summary dataset can be provided as supplementary material or deposited in a recognised repository if required by the editor. No external funding was received for this manuscript. The framework represents the author's scholarly analysis and does not represent an official position of any employer, government body, or project.

IV. LITERATURE SYNTHESIS

A. From lagging performance to leading and predictive safety

Traditional safety measurement relies heavily on injuries, lost time, severity, and incident counts. These remain important outcome indicators but are intrinsically retrospective. Hallowell and colleagues, and Hinze and colleagues, demonstrated the value of leading indicators that measure safety-related practices before injuries occur (Hallowell et al., 2013; Hinze et al., 2013). More recent reviews continue to support an ecosystem perspective that combines organisational, operational, and behavioural signals rather than relying on a single metric (Xu et al., 2021).

The trajectory of safety measurement can be represented as five progressive generations, each retaining the value of the one before it.

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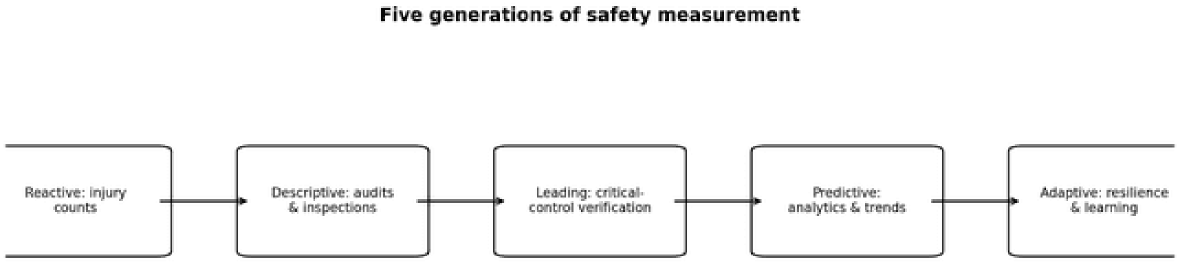

Figure 3. Five generations of safety measurement, from lagging outcomes to adaptive capacity.

For Vision 2030 projects, the practical implication is not to discard lagging indicators but to build a layered measurement system. Critical-control verification, permit quality, exposure exceedances, supervisor field engagement, design-risk closure, equipment-state alarms, and corrective-action ageing can all provide earlier evidence of changing risk. Predictive analytics can then identify patterns requiring attention, but such analytics should remain decision support rather than autonomous safety authority.

B. Safety climate, leadership and worker participation

Saudi construction research provides a strong basis for keeping human and organisational factors at the centre of the framework. Studies involving 401 construction personnel identified supervision, hazard appraisal, management commitment, safety justice, communication, training, worker involvement, and supportive environments as important safety-climate factors (Makki & Mosly, 2020; Mosly & Makki, 2020). A predictive model using the same data set identified supervision, management commitment, management safety justice, coworker influence, and social-security/health-insurance factors among significant predictors of safety-climate evaluation (Makki & Mosly, 2021). These findings remain consistent with the foundational safety-climate literature, in which shared perceptions of management priority and expected behaviour shape safety motivation and behaviour (Zohar, 1980).

Notably, the machine-learning safety literature independently converges on organisational and supervisory variables. A study predicting serious injury and fatality exposure conditions found that the most influential factors were the crew's experience working together, the supervisor's experience with that crew, the total number of workers under the supervisor's purview, and the maturity of leadership development programmes for frontline supervisors; the authors also showed that datasets containing both success and failure information yield more reliable predictions than failure-only datasets (Erkal et al., 2023). This is a useful corrective to purely sensor-driven safety models: measurement sophistication does not replace supervisory quality.

For a diverse workforce, participation cannot be limited to toolbox talks. A mature system requires accessible reporting, multilingual communication, stop-work confidence, feedback closure, and demonstrable evidence that worker concerns influence planning.

C. Occupational health and cumulative exposure

Safety systems often measure acute injury more visibly than chronic occupational-health burden. Yet work-related ill-health can develop through repeated exposure to heat, noise, dust, chemicals, vibration, ergonomic stressors, and fatigue. WHO/ILO joint estimates indicate that workplace risk factors contribute substantially to disability-adjusted life years and premature mortality, with disease accounting for a large share of the overall work-related burden, and EU-OSHA's Workers' Exposure Survey reported that more than 60% of workers in construction and mining/quarrying had probable

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exposure to at least two selected occupational cancer risk factors (Abdul Salam, n.d.).

A transformation framework therefore requires worker exposure profiles, job-exposure matrices, health surveillance where legally and ethically appropriate, and trend analysis that links work history to exposure controls. Related work on longitudinal exposure management argues for a Worker Exposure Profile approach and explicitly rejects cross-hazard aggregation: silica, noise, vibration, chemicals, heat, and fumes retain their own measurement systems, limits, and interpretation (Abdul Salam, n.d.). This design principle matters because a single composite "exposure score" would obscure the agent-specific controls and legal limits that govern each hazard.

Practitioner evidence supports the demand but exposes the operational deficit. In a survey of 65 HSE professionals and industry specialists drawn from oil and gas, infrastructure, and urban development, longitudinal exposure management scored 4.34 out of 5.0 and the Worker Exposure Profile concept 4.18 out of 5.0, while data continuity — the loss of exposure history as workers move between employers — recorded the lowest construct mean at 3.77 out of 5.0 (Abdul Salam, unpublished practitioner survey). The same respondents ranked welding fumes (93.8%), respirable crystalline silica (89.2%), and noise (81.5%) as the most frequently selected priority exposures, followed by hand-arm vibration (72.3%), paints and solvents (64.6%), ergonomic strain (61.5%), heat stress (50.8%), and whole-body vibration with diesel exhaust (41.5%) (Abdul Salam, unpublished practitioner survey).

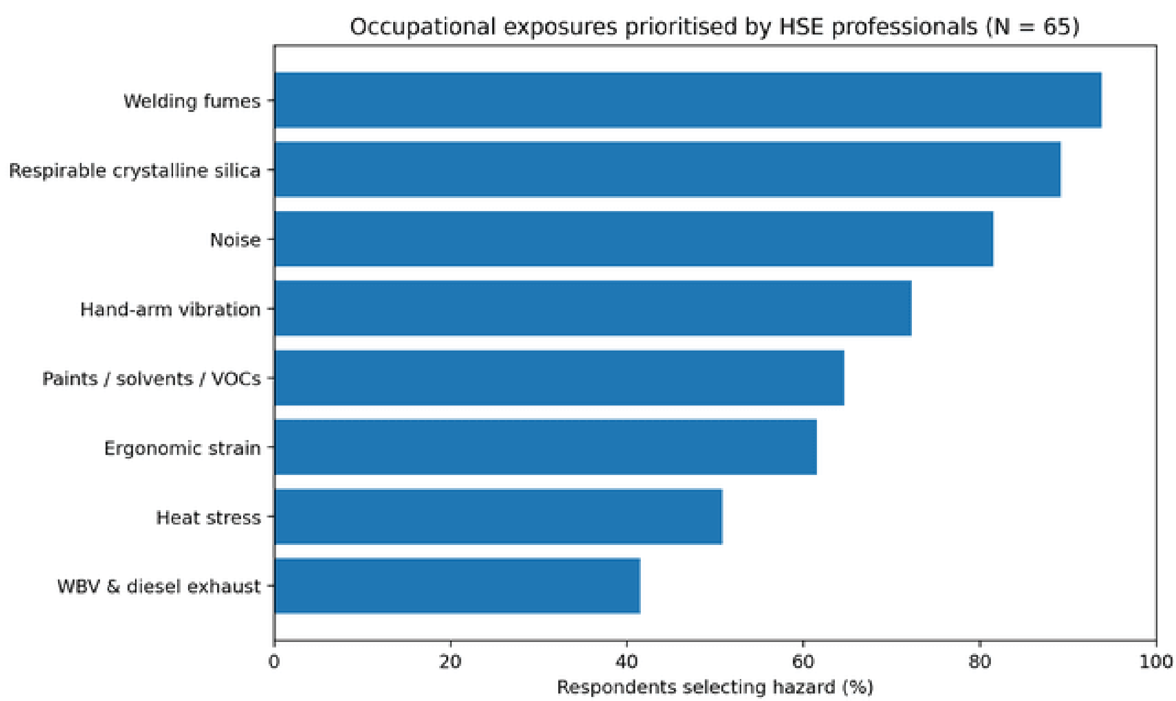

Figure 4. Exposure hazards prioritised by 65 HSE professionals and industry specialists, by percentage of respondents selecting each hazard.

The barriers to continuous exposure management were equally diagnostic: lack of management priority accounted for 40.0% of responses (n = 26), poor exposure-record continuity 26.2% (n = 17), lack of occupational-health knowledge 16.9% (n = 11), and the combined cost of monitoring and worker mobility 16.9% (n = 11) (Abdul Salam, unpublished practitioner survey). Notably, the dominant barrier is organisational rather than technical — chronic risks with long latency periods lose priority to immediate compliance concerns — which reinforces the framework's decision to place governance, management commitment, and data continuity around, rather than beneath, the technology layer.

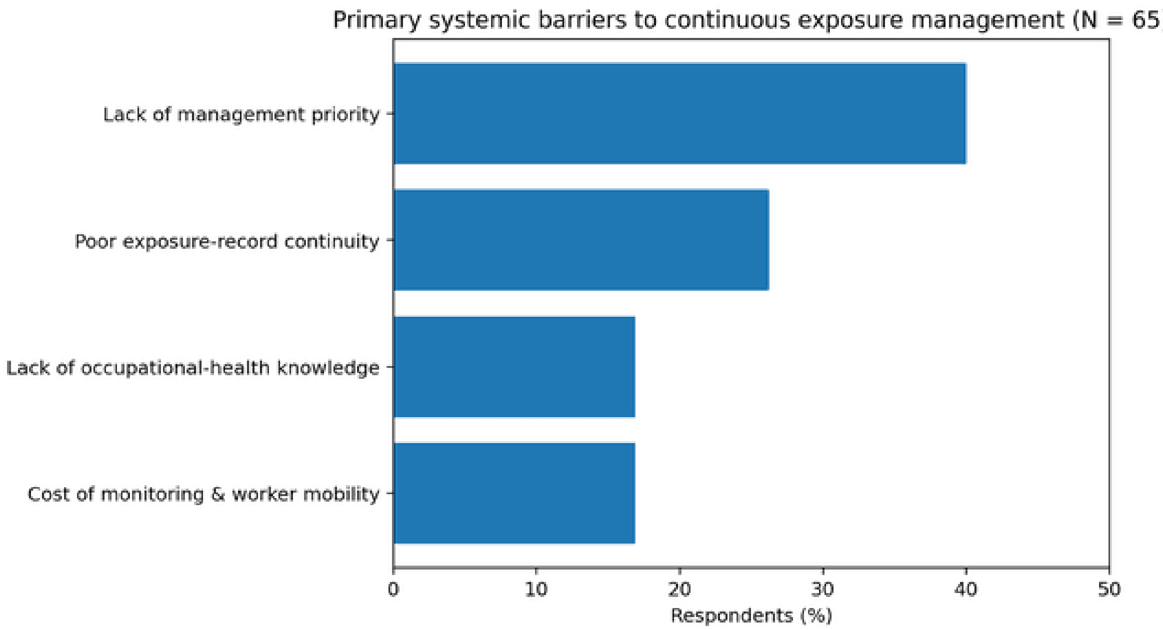

Figure 5. Primary systemic barriers to continuous exposure management, by share of respondents.

In the Saudi context, heat deserves particular attention, because climatic conditions can amplify fatigue and physiological strain during outdoor work. The relevant management shift is from a single ambient threshold to a layered exposure model considering workload, clothing and PPE, acclimatisation, hydration, recovery quality, work duration, and individual warning signs. Personal health data, if used, require strict purpose limitation, access control, and privacy safeguards.

D. Digital safety, IoT, wearables and AI

Digital safety technologies can extend observation beyond periodic inspections. Reviews document applications of wearables and IoT in fall detection, environmental sensing, fatigue and physiological monitoring, location awareness, hazard identification, and activity recognition (Awolusi et al., 2018; Babalola et al., 2023; Chen et al., 2023; Kim et al., 2024). Saudi studies published in 2026 similarly indicate growing interest in IoT and wearables, while identifying adoption barriers and underscoring the importance of socio-technical integration (Mosly, 2026).

Commercially deployed devices cluster into identifiable families: smart helmets and safety vests (the most recognised category among Saudi respondents), fatigue and environmental sensors, gas and atmospheric detectors, proximity and geofence devices, and fall-detection units (Mosly, 2026). A Saudi review of IoT and AI implementation across energy, petrochemical, construction, mining, and logistics concluded that real-time PPE monitoring through computer vision and wearable sensing technology are both considered useful contributions to the safety-management process, with the potential to shift management from reactive to proactive (Ahmad et al., 2026).

Digitalisation, however, introduces new failure modes. Poor sensor quality, false alarms, battery limitations, connectivity gaps, cybersecurity exposure, algorithmic bias, and privacy concerns can all undermine trust. An AI-augmented safety paradigm explicitly identifies data-quality anomalies, model generalisation, alert fatigue, and the ethical and surveillance implications of continuous monitoring as core implementation risks requiring responsible-deployment practices (Mohammed et al., 2025).

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Construction-specific privacy research highlights the risks associated with continuous location and health monitoring (Okonkwo et al., 2024). Digital safety should therefore be governed by clear data ownership, minimal necessary collection, transparent purposes, retention rules, and human review of automated alerts.

E. Prevention through Design and lifecycle safety

Construction risk is strongly influenced by decisions made before workers arrive on site. Prevention through Design shifts risk reduction upstream by considering construction, operation, maintenance, and decommissioning hazards during design. Research has demonstrated the conceptual and practical value of PtD, while noting persistent implementation challenges and the need for stronger integration with digital design tools (Gangolells et al., 2010; Samsudin et al., 2021).

The BIM literature extends this argument into practice. Work on Saudi public-sector construction proposes a BIM-based framework for automated hazard identification and correction during both design and construction, and advocates BIM specifically as a means of communicating with a predominantly migrant workforce — linking design-stage risk elimination to language and literacy realities (Balgheeth, 2016). A subject review of PtD studies reaches a consistent conclusion: the concept is well established, but its routine application still depends on collaboration between designers and constructors and on digital tool integration (Jin et al., 2022).

For Vision 2030 assets, lifecycle safety is especially relevant because infrastructure being created today will be operated and maintained for decades. Design reviews can therefore address access for maintenance, lifting points, isolation philosophy, confined-space elimination, permanent fall protection, safe replaceability of components, emergency access, and human factors.

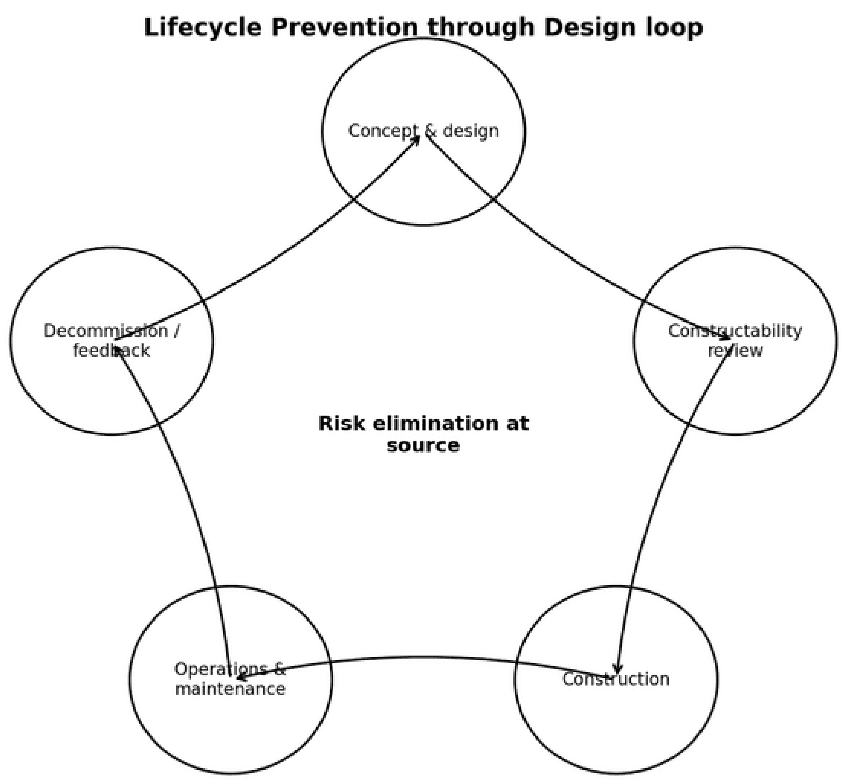

Figure 6. Lifecycle Prevention through Design loop, with lessons returning to future design reviews.

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F. Resilience, learning and adaptive capacity

Resilience engineering reframes the safety question from "why did failure occur?" to "how does the system continue to succeed under variable conditions?" Hollnagel describes resilience through the capacities to respond, monitor, learn, and anticipate (Hollnagel, 2018). These concepts are valuable for complex projects in which simultaneous operations, changing plant states, night work, heat, temporary systems, and contractor interfaces create continuous variability.

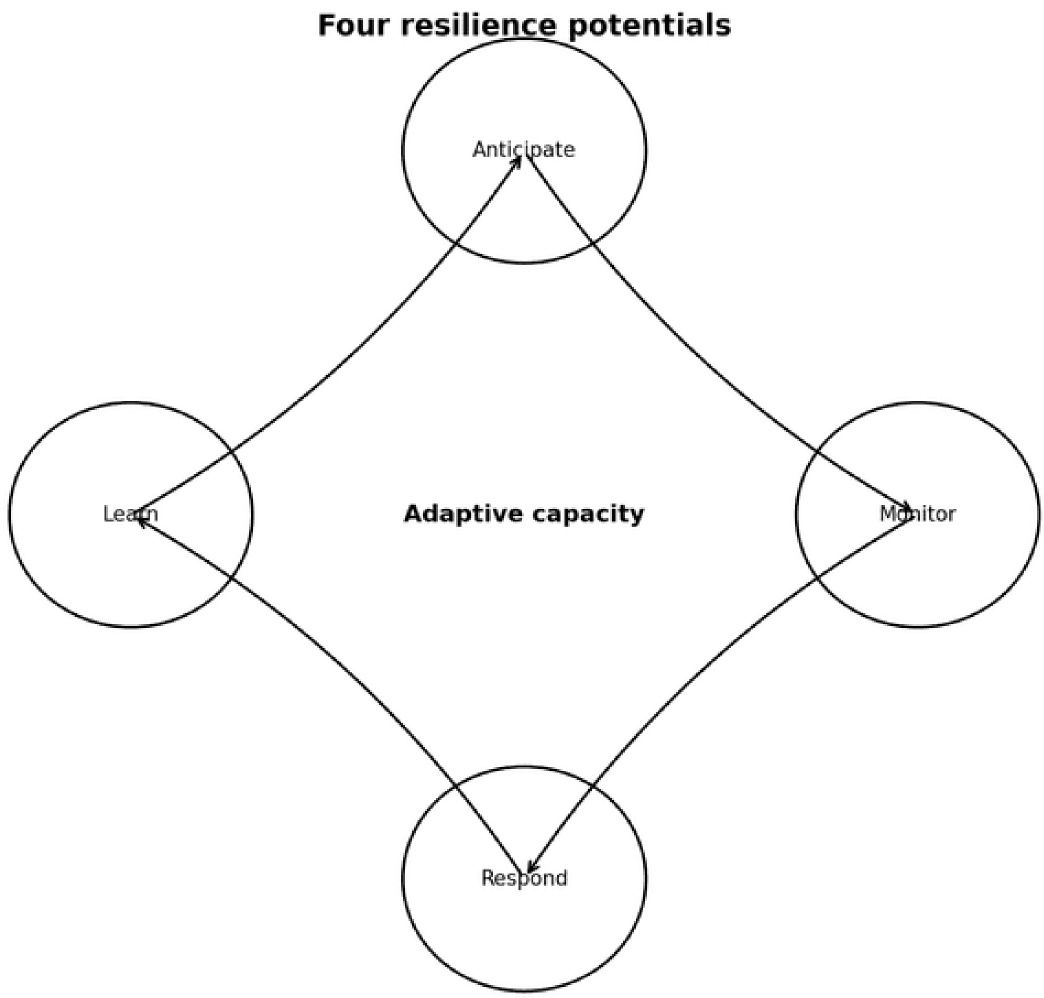

Figure 7. The four resilience potentials applied as an operating cycle.

A resilient Saudi OSH model therefore needs both formal controls and operational sensing. It should detect weak signals, monitor critical assumptions, learn from successful adaptations as well as from incidents, and maintain readiness for credible emergencies. This is particularly relevant to brownfield, commissioning, restoration, and live-plant interfaces, where static risk assessments can become outdated quickly.

G. Computer vision and automated hazard detection

Computer vision is the most mature entry point for automated observation on construction sites. A study training the YOLO-v5 object-detection model on a purpose-built dataset demonstrated recognition of construction workers, their PPE, and surrounding heavy equipment from CCTV footage, with hazards inferred from imagery combined with contextual criteria such as weather conditions and routed to an on-site safety officer (Alateeq et al., 2023). Subsequent work using YOLOv8 reported the ability to recognise nine categories of safety equipment, with the greatest accuracy of 0.94 when tested across 100 epochs, and an alerting mechanism that notifies the project engineer immediately when anomalies are detected (Alateeq et al., 2023; Mohy et al., 2024, 2025).

A scientometric analysis of the field confirms that computer vision and deep learning are effective for identifying hazards and monitoring PPE use, with the potential to reduce accidents and injuries (Mohy et al., 2024). However, the same literature stream is candid about the constraints. Three recurring challenges are identified: dataset limitations, where publicly available datasets lack the scale, diversity, and specific hazard categories — such as scaffolding faults and unsafe actions — needed to train robust models; algorithmic limitations, because standard object-detection models are not inherently optimised for severe occlusion, varying illumination, and subtle contextual hazards; and practical implementation, where many proposed models are either too computationally heavy for real-time deployment or insufficiently accurate, while integration into existing workflows requires attention to human–computer interaction, data privacy, and algorithmic bias (Mohy et al., 2025).

A practical computer-vision deployment therefore requires a disciplined pipeline rather than a camera installation.

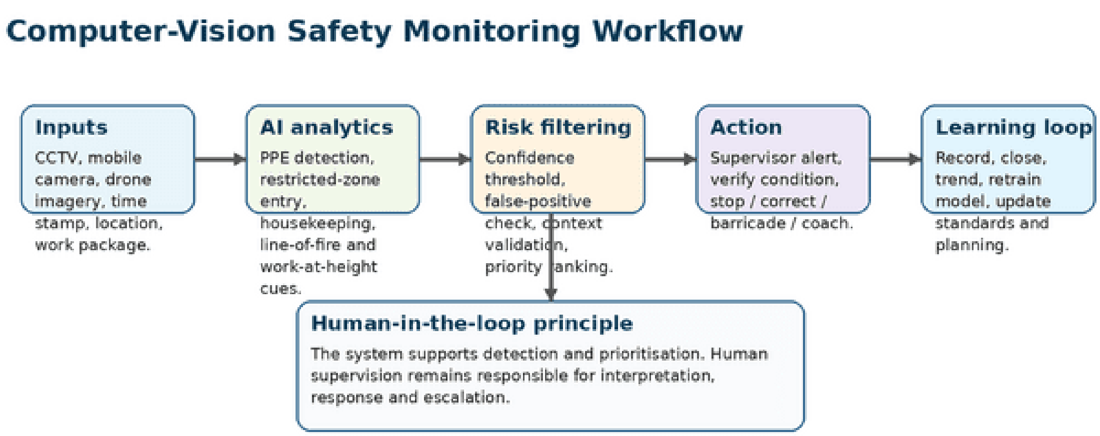

Figure 8. Computer-vision hazard-detection pipeline with a human verification step and a feedback loop into the rule layer.

Three design principles follow from the evidence. First, detection should trigger a human verification step, not an automatic sanction, because false positives erode trust and accelerate alert fatigue (Mohammed et al., 2025). Second, models should be validated against local site conditions — occlusion patterns, PPE variants, lighting, and dust — rather than adopted on vendor accuracy claims alone (Mohy et al., 2025). Third, imagery and inferred behavioural data are personal data; retention, access, and purpose must be defined before deployment, not after a privacy objection arises.

1) Regional environmental robustness parameters

For Saudi deployment, extreme environmental conditions should be treated as a model-validity state rather than only as an equipment-maintenance issue. Construction-object-detection research shows that performance can decline under intense light, low light, suspended dust, fog, and rain, and that robustness improves when these conditions are represented explicitly during training and validation (Ding et al., 2024; Gyawali et al., 2026). Accordingly, any computer-vision pilot under the SV2030-OSTF should report precision, recall, mAP50, and false-positive rate separately for clear daylight, intense glare/backlighting, low-light/night work, dust/sand loading, and partial occlusion/high-density activity rather than relying on a single aggregate accuracy value.

The framework therefore proposes the following regional engineering controls as pilot design parameters rather than universal regulatory limits. The values are intended to be tuned against site data and manufacturer limits before operational use.

TABLE II. ILLUSTRATIVE ENVIRONMENTAL ROBUSTNESS PARAMETERS FOR SAUDI CONSTRUCTION DEPLOYMENTS

Edge case	Illustrative technical parameter / control	Operational response
Intense sun / glare	Include glare and overexposure in validation data; physics-based bright-sun augmentation may use multiple severity states such as 1.3, 1.5 and 1.8 intensity factors reported in recent YOLOv8n work. Use WDR/high-light compensation where available.	If the image-quality gate detects excessive saturation or loss of contrast beyond the locally validated range, downgrade automatic alerts to advisory status and request human verification.
Sand / suspended dust	Use locally captured dust/sand images plus synthetic dust/fog augmentation. Outdoor camera and edge-sensor enclosures should be selected to an IEC 60529 ingress-protection class appropriate to the exposure; IP66 is a practical baseline for fixed outdoor units, with higher protection where washdown or temporary immersion is credible.	Monitor lens obstruction / scene contrast. A failed image-quality check creates a device-health alert and prevents the system from treating “no detection” as proof of compliance.
High ambient heat	Select cameras, gateways and sensors with a manufacturer-rated operating envelope that covers the verified site ambient/enclosure temperature. Configure a temperature-health warning at 90% of the rated upper limit and a degraded/fail-safe mode at the rated limit.	Maintain local sensing and manual controls; shed non-critical analytics before safety-critical sensing. Do not allow thermal throttling to silently reduce detection frequency.
Night / low light	Validate against project-specific night lighting, shadow, motion blur and reflective PPE. Weather-resistant YOLOv8n research shows that low-light performance can be materially improved through condition-specific augmentation.	Use illumination/IR only where suitable for the use case; require human confirmation when model confidence falls below the validated night-work threshold.
Crowding / occlusion	Test far-field views, overlapping workers and partial PPE visibility as separate acceptance cases; recent PPE-detection research identifies far-field views and worker overlap as persistent failure modes.	Combine temporal tracking, zone context and supervisor confirmation rather than generating repeated frame-by-frame alerts.

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2) Alert-fatigue triage and human-in-the-loop thresholds

Alert management should be designed as a triage workflow rather than a direct translation of every model detection into an alarm. The proposed workflow has four gates: (1) a device-health and image-quality gate; (2) a detection-confidence and temporal-persistence gate; (3) a risk-priority gate based on consequence, time to harm, and work-zone context; and (4) a human verification step before any personnel sanction or formal non-conformance is issued. This approach is consistent with alarm-management principles that emphasise prioritisation, rationalisation, actionable notifications, and monitoring of nuisance alarms, while preserving human oversight for AI-supported safety decisions.

For an initial field pilot, the framework recommends illustrative defaults that must be re-tuned using local precision-recall analysis: a candidate computer-vision event at confidence ≥0.60; automatic escalation at confidence ≥0.80 when the event is safety-critical, or at lower confidence when corroborated by a second independent signal such as geofencing, PTW status, or proximity sensing; persistence across at least three consecutive frames or approximately 1–2 seconds for non-immediate conditions; and duplicate suppression for 60 seconds after acknowledgement. Immediate life-critical conditions—such as a person entering an active exclusion zone—may bypass the persistence delay when independently corroborated. These values are proposed starting points, not validated universal thresholds.

Alert quality should itself be a KPI. The control room should track actionable alerts per operator per 10-minute interval, false-positive ratio, repeat-alert ratio, median acknowledgement time, and percentage of alerts that result in a verified intervention. Sustained growth in alert rate without a corresponding rise in verified interventions should trigger rule recalibration, shelving of nuisance alerts, or retraining of the model rather than additional operator burden.

H. Digital twins and BIM-integrated safety intelligence

A digital twin for construction safety connects the physical site to a continuously updated model, allowing risk to be interrogated rather than merely recorded. The concept of a Digital Twin for Construction Safety has been formalised as three essential workflow steps: safe design and planning for hazard prevention; risk monitoring and control for proactive prediction and warning; and continuous performance improvement supporting personalised or project-based learning (Teizer et al., 2022). This definition is important because it frames the digital twin as a system-based approach to safety performance, not simply as sensing information embedded in a BIM model.

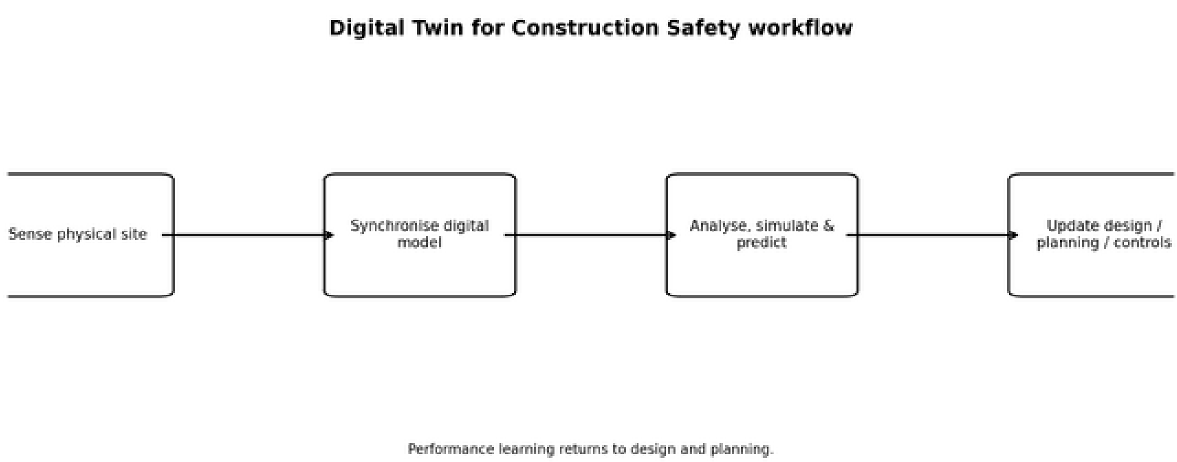

Figure 9. Three-step Digital Twin for Construction Safety workflow, with performance learning returning to design and planning.

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A systematic review of digital twin applications in construction safety risk management identified five application areas: real-time monitoring and early warning, safety risk prediction and assessment, accident simulation and emergency response, safety risk management decision support, and safety training and education — while concluding that application remains at an early stage (Luo et al., 2024). A review of digital twins for workforce safety reached a similar verdict: despite demonstrated effectiveness in improving construction workforce safety, the industry has yet to fully exploit and streamline these innovations in practice (Hou et al., 2020).

Implementation studies show what the architecture looks like in practice. A proposed digital replica for safety surveillance combines 4D BIM models, cloud computing and database platforms, and real-time field data captured by sensors and processed by artificial intelligence, enabling safety managers to receive real-time analyses and predictions based on site conditions (Shariatfar et al., 2022). The AI-augmented paradigm extends this by combining computer vision for PPE detection and unsafe-behaviour recognition, wearable sensor analysis for fatigue and stress monitoring, and predictive machine-learning models for incident prediction, with BIM and digital twin integration enabling real-time hazard mapping and simulation (Mohammed et al., 2025).

The governance implication is significant. Blockchain and digital twin integration research, synthesising 114 articles, identifies five key challenges — data integration and interoperability, data quality and trustworthiness, cost and resource constraints, privacy and security concerns, and change management and cultural shift — and four critical gaps: the absence of standards and protocols, the need for consensus methods, exposure to cyberattacks and security breaches, and the immaturity of decentralised digital twins (Manzoor et al., 2026). A digital twin that is fed by unreliable data will produce authoritative-looking but unreliable warnings; trustworthiness is therefore a safety property, not merely an IT property.

I. Immersive training and XR-enabled competence

Extended reality — virtual, augmented, and mixed reality — offers a route to competence that is difficult to achieve through classroom delivery alone, particularly for a multilingual workforce. A content review of 74 journal papers traced the evolution of XR construction training across five areas: safety management, skill and knowledge acquisition, equipment operation, human–computer collaboration, and ergonomics and postural training (Li et al., 2024).

The effectiveness evidence is encouraging but nuanced. A controlled study with 66 subjects found that immersive VR training produced significant advantages over conventional classroom training for stone cladding work and cast-in-situ concrete work, though not for general site safety, while also sustaining trainee attention and concentration more effectively and retaining its advantage over time (Sacks et al., 2013). A systematic review and meta-analysis of 52 articles concluded that VR safety training outperforms traditional training in knowledge acquisition and retention — but also found that only 9.6% of studies explicitly adopted a theory when developing and testing their applications, and only 36% provided long-term retention data (Scorgie et al., 2023). A further review of 41 studies across high-risk industries identified persistent human and socio-technical challenges including limited viewing fields, motion sickness, and control issues (Dodoo et al., 2025). Evaluation practice itself remains unstandardised, with construction safety XR experiences assessed through a mix of objective and subjective methods that vary widely between studies (Salinas et al., 2022).

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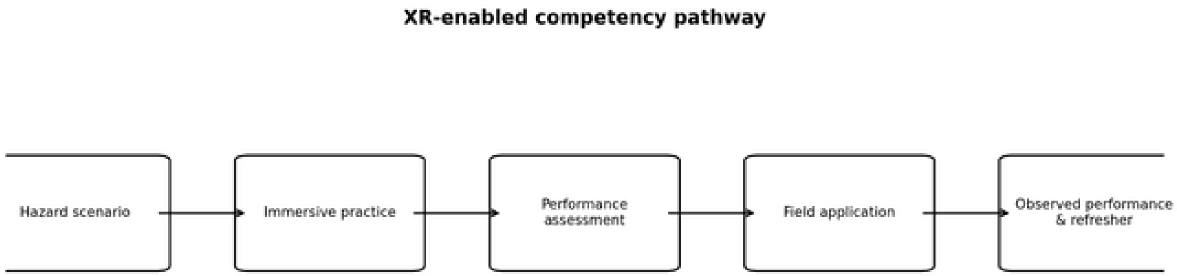

Figure 10. XR-enabled competency pathway, closing the loop between simulated and observed field performance.

The design conclusion is that XR should be treated as an assessment and rehearsal instrument within a competency system, not as a training deliverable to be counted by hours completed. Where it is used, retention testing should be scheduled rather than assumed, and scenarios should be derived from the organisation's own incident, near-miss, and permit data so that they reflect local risk.

J. Assistive robotics and exoskeletons

Musculoskeletal disorders caused by overexertion, repetitive work, heavy lifting, and sustained postures remain a leading category of construction injury, and exoskeleton technology is proposed as a means of augmenting strength, mobility, and endurance while improving workplace ergonomics (Linner et al., 2018). Quantitatively, the labour-intensive nature of construction exposes workers to musculoskeletal injury at approximately 31.2 cases per 10,000 full-time-equivalent workers, and exoskeletons and exosuits are designed to reduce exertion and muscle fatigue during work (Bennett et al., 2023).

Adoption evidence, however, is mixed and markedly more cautious than vendor material suggests. A field-based pilot in a real construction workplace tested a back-support exoskeleton with four experienced workers performing gondola push/empty tasks and two arm-support exoskeletons with three workers installing and removing wooden blocks; workers responded differently to the devices and were not unanimously in favour of adoption in practice, and the authors note that prior assessments were mainly conducted in laboratories with participants who were not construction professionals (Bennett et al., 2023). Stakeholder research groups industry concerns into expected benefits, technology adoption factors, and perceived barriers, with uncertainties expressed about practical value, usability, and the impact of exoskeletons on worker safety (Kim et al., 2019).

The framework therefore treats exoskeletons as an ergonomic control under evaluation rather than a settled solution, appropriate to specific high-exertion tasks with defined trial criteria (task time, posture, heart rate, perceived exertion, and worker acceptance). Robotics and automation more broadly form one of the key Industry 4.0 pillars relevant to construction, alongside data analytics and AI, BIM, sensors and wearables, digital twin, and industrial connectivity (Turner et al., 2020).

K. Connectivity, blockchain and data trust

The value of individual safety technologies depends on the connectivity layer that allows them to exchange data. Reviews of construction digitalisation place cloud, fog, and edge computing alongside IoT devices such as smartphones, sensors, robots, and cameras as the infrastructure that delivers the dependability required by time-critical site functions including worker location tracking, BIM integration, and construction monitoring — while noting unresolved tensions between fast application performance, low-cost operation, and the competing demands of data fusion and data privacy (Radman et al., 2022).

Blockchain has been proposed as a complementary trust layer for safety records, and blockchain–digital twin integration research identifies three research areas — accident prevention and management, data-driven decision-making, and wearable technologies for proactive safety monitoring — alongside the interoperability, cost, privacy, and change-management challenges noted earlier (Manzoor et al., 2026). Realistically, for most Saudi projects the near-term priority is not distributed ledger technology but basic interoperability: common definitions, reliable capture, traceable data provenance, and the ability to join permit, exposure, inspection, and training data without uncontrolled duplication.

V. THE SAUDI VISION 2030 OCCUPATIONAL SAFETY TRANSFORMATION FRAMEWORK (SV2030-OSTF)

The proposed framework comprises seven dimensions. They are intentionally interdependent: no single pillar is sufficient, and digital technologies are positioned as one component within a broader socio-technical safety system.

Figure 11. The seven-dimension SV2030-OSTF architecture and its cross-cutting enablers.

A. Dimension 1 – Governance and assurance

Governance converts intent into consistent accountability. This dimension covers policy, role clarity, regulatory alignment, contractor requirements, critical-risk standards, assurance, audit quality, incident-reporting governance, and executive oversight.

At project level, governance should define who owns each critical control, who verifies it, what evidence is acceptable, and how unresolved deviations are escalated. At ecosystem level, common definitions and interoperable reporting structures can reduce fragmentation between owners, contractors, and subcontractors — a decisive issue in a delivery environment characterised by fragmentation and multi-tier contracting (Balgheeth, 2016).

Indicative practices include contractor prequalification based on leading indicators, independent assurance of high-risk controls, a common taxonomy for incidents and exposures, visible leadership review of health as well as safety, and management-of-change requirements when schedule, scope, design, or work interfaces materially change.

B. Dimension 2 – Predictive risk intelligence

This dimension shifts the operating model from periodic inspection toward continuous risk sensing.

Data sources may include permits, simultaneous-operations maps, observations, critical-control checks, equipment alarms, exposure monitors, weather data, training status, work-hour patterns, and corrective-action ageing.

Predictive risk intelligence does not require sophisticated machine learning at the first maturity stage. Basic trend detection, thresholds, and risk aggregation can already deliver significant value. Advanced analytics should be introduced only once data quality, definitions, and governance are stable — a sequencing judgment supported by the digital-twin literature's emphasis on data trustworthiness and interoperability (Manzoor et al., 2026).

One example is a daily dynamic risk picture that combines planned high-risk permits, lifting zones, confined-space entries, hot work, traffic routes, and heat conditions to identify interaction hotspots before work begins.

The machine-learning evidence base is now sufficiently mature to justify this dimension. Applying Random Forest and Stochastic Gradient Tree Boosting to injury narratives processed by natural language processing predicted injury type, energy type, and body part with predictive skill between 0.236 and 0.436, outperforming the parametric models in prior literature; the authors concluded that injuries do not occur at random and that construction safety can be studied quantitatively, though the absence of predictive skill for injury severity suggested that severity may be substantially random or require additional contextual information (Tixier et al., 2016). A Saudi study using 203 incidents from 2018–2024 with 14 explanatory variables and six algorithms found that all models exceeded 60% accuracy, with Extreme Gradient Boosting performing best at 89% accuracy for severity prediction, where interpretability analysis identified incident nature, precipitation, date, and workforce size as the most influential predictors, with location, safety training, and PPE compliance contributing additional explanatory power (Alsulamy et al., 2026). Comparative work has also moved toward large language models: one study reported XGBoost and an LLM classifier achieving accuracies of 97.9% and 94.5% and recalls of 97.5% and 98.9% respectively, with temporal robustness confirmed on 1,206 hold-out datasets (Park et al., 2026).

These results argue for a staged analytics strategy: begin with descriptive and threshold-based indicators, progress to classical supervised models on the organisation's own incident and observation data, and consider more complex or language-model-based approaches only where interpretability, validation, and human oversight can be maintained.

C. Dimension 3 – Occupational health and exposure prevention

This dimension gives chronic and cumulative health risk equal status with acute injury prevention. Core elements include exposure inventories, similar-exposure groups, heat-stress programmes, noise and vibration control, respiratory hazards, chemical exposure, ergonomics, fatigue, and health surveillance where appropriate.

A mature system would move from task-only exposure assessment toward longitudinal exposure profiles. The purpose is preventive: to identify when repeated "acceptable" exposures may accumulate into a meaningful risk pattern and to intervene through elimination, substitution, engineering controls, work design, and recovery. Because workers move between tasks, work fronts, contractors, and project phases, the continuity of the exposure record — not the sophistication of the sensor — is the binding constraint; data continuity recorded the weakest construct score in the practitioner survey, while longitudinal management recorded the strongest (Abdul Salam, unpublished practitioner survey).

Health data must be treated with stronger confidentiality than ordinary safety observations. Only necessary information should be used for prevention, and clinical interpretation should remain with qualified health professionals. Where agent-specific records are maintained, they should preserve the distinct measurement systems and occupational exposure limits applicable to each hazard rather than being aggregated into a composite index (Abdul Salam, n.d.).

D. Dimension 4 – Human capability, leadership and worker voice

This dimension recognises that competence is more than holding a certificate. It encompasses task knowledge, hazard recognition, decision quality, supervisory capability, communication, language accessibility, fatigue awareness, and the confidence to stop or challenge unsafe work.

Leadership is measured through decisions and resource allocation rather than statements alone. Relevant indicators include supervisor field presence, quality of pre-task planning, response time to worker concerns, closure of repeated issues, and whether production decisions are changed when controls prove inadequate. This emphasis is empirically supported: supervisory experience with the crew, crew experience working together, and the span of workers under a supervisor's authority were among the strongest predictors of serious injury and fatality exposure conditions in a machine-learning study, alongside the maturity of frontline supervisor leadership development (Erkal et al., 2023).

Worker voice mechanisms should provide multiple channels: face-to-face escalation, confidential reporting, digital reporting, stop-work authority, and feedback on how concerns were resolved. For a multilingual and multi-ethnic workforce, visual and BIM-based communication can complement written instruction (Balgheeth, 2016), and XR scenarios can rehearse hazard recognition in the worker's own language without exposing them to live risk (Li et al., 2024).

E. Dimension 5 – Digital safety and connected worksites

Digital safety covers IoT, wearables, computer vision, drones, digital permits, geofencing, BIM and 4D models, connected equipment, and AI-supported analysis. The objective is to increase visibility of risk, not to increase surveillance for its own sake.

Technology adoption should follow a use-case approach. Each deployment should define the hazard addressed, the required accuracy, the human response, the fallback if the technology fails, ownership of data, cybersecurity controls, and criteria for demonstrating benefit.

High-value applications in Saudi high-risk work may include heat and environmental sensing, proximity alerts around mobile plant, lifting-zone geofencing, fall and tie-off verification, gas monitoring, digital isolation verification, and integration of permit data with SIMOPS planning. Drone-based inspection is a further supported application: surveyed practitioners ranked monitoring boom vehicles and cranes in proximity to overhead power lines, monitoring activities near such plant, and monitoring unprotected edges or openings as the most valuable safety activities for unmanned aircraft systems, with camera movability, sense-and-avoid capability, and a real-time video feed identified as the most important technical features (Elghaish et al., 2020). Integration models combining 4D BIM with UAV monitoring have been developed and evaluated by safety specialists, with the reported rationale that design-phase and construction-phase safety are joined rather than treated separately (Akinsemoyin et al., 2024; Alizadehsalehi et al., 2018).

F. Dimension 6 – Prevention through Design and lifecycle safety

Safety should be embedded before construction and continue through commissioning, operations, maintenance, and eventual decommissioning. Design-risk reviews should consider not only end-user safety but also the people who construct, inspect, clean, repair, and replace assets.

Design-stage deliverables can include lifecycle hazard registers, safe-maintenance access reviews, engineered anchorage provisions, permanent lifting points, isolation strategy, confined-space minimisation, modularisation opportunities, and constructability risk reviews.

BIM and digital twins can strengthen this dimension when used to visualise access, sequencing, temporary works, and high-risk interfaces before execution. The strongest formulation in the literature treats the digital twin as beginning with safe design and planning rather than with site sensing, so that hazard prevention precedes hazard detection (Teizer et al., 2022).

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G. Dimension 7 – Resilience, learning and operational readiness

This dimension addresses changing conditions and the ability to recover when assumptions fail. It includes emergency readiness, operational learning, management of change, learning teams, weak-signal reporting, after-action reviews, and monitoring of system capacity.

Rather than limiting learning to adverse events, organisations can review successful complex work to identify which adaptations made performance safe. This supports a balanced Safety-I/Safety-II approach: preventing known failure modes while strengthening the capacity to handle variability (Hollnagel, 2018).
Readiness indicators can include emergency drill effectiveness, backup-system availability, competence coverage for night shifts, response time to critical alarms, management-of-change quality, and whether lessons are incorporated into future planning.

H. Cross-cutting enablers

- Data governance and interoperability: common definitions, reliable data capture, traceable sources, and the ability to combine information across systems without creating uncontrolled duplication. Interoperability and data quality were the first two challenges identified in blockchain–digital twin research (Manzoor et al., 2026).
- Competency architecture: role-based requirements for workers, supervisors, designers, HSE professionals, engineers, and leaders, with emphasis on demonstrated capability rather than attendance alone.
- Ethics, privacy and trust: proportional data collection, worker transparency, human review, cybersecurity, and limits on repurposing health or location data. Alert fatigue and surveillance concerns are documented risks in AI-enabled safety systems (Mohammed et al., 2025).
- Climate adaptation: heat, weather, dust, and environmental variability incorporated into planning, exposure management, and emergency readiness.
- Connectivity and cyber resilience: edge, fog, and cloud infrastructure designed with the performance and privacy trade-offs of time-critical site systems in mind (Radman et al., 2022).

I. Technology-enabled safety intelligence architecture

Many digital-safety initiatives stall because individual tools are deployed without an integrating architecture. The framework therefore specifies a five-layer safety intelligence architecture in which each layer has an explicit safety purpose, and assurance closes the loop back to sensing.

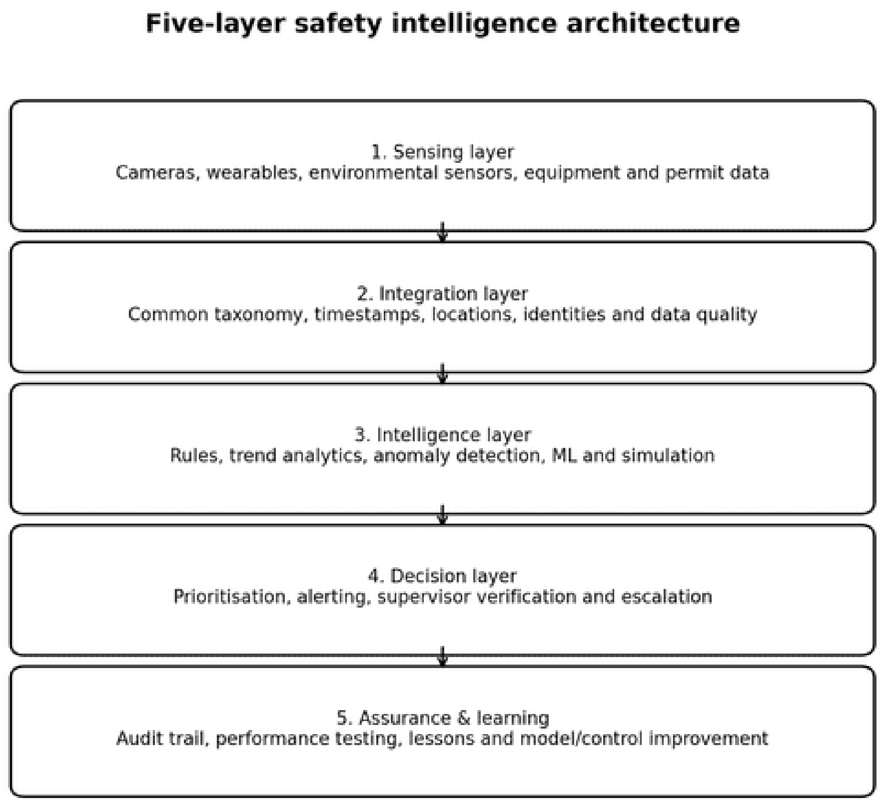

Figure 12. Five-layer safety intelligence architecture, with assurance returning insight to the sensing layer.

Each layer carries a corresponding governance obligation. Layer 1 requires purpose limitation and data-minimisation decisions before devices are issued. Layer 2 requires a documented fallback when connectivity fails, since a safety system that becomes unavailable during a heat event or a network outage is a new hazard rather than a control. Layer 3 requires documented accuracy, validation, and interpretability standards, together with human review of automated outputs (Mohammed et al., 2025). Layer 4 requires that alerts map to a named role with the authority and resources to act. Layer 5 requires that verification is independent of the function being verified. Table 6 operationalises that requirement by defining which functions remain local, which pause, and how records are reconciled after recovery.

1) Offline and degraded-connectivity operating mode

Remote work fronts and geographically dispersed gigaproject sectors cannot assume continuous cloud connectivity. The five-layer architecture is therefore designed so that loss of the wide-area network degrades convenience before it degrades critical safety functions. Edge-enabled construction research supports local processing, autonomous event triggering and queue-based prioritisation as ways to reduce cloud dependence and preserve low-latency hazard response (Chen, 2020; Lee & Hsieh, 2026).

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TABLE III. OFFLINE/DEGRADED-MODE OPERATING MATRIX FOR THE FIVE-LAYER SAFETY INTELLIGENCE ARCHITECTURE

Architecture layer	Normal connected mode	Offline / degraded mode	Recovery requirement
Layer 1 – Sensing	Continuous sensors, cameras, wearables and equipment state feed the edge/cloud stack.	Continue local acquisition and timestamping. Safety interlocks and local warning devices must not depend on the cloud. Store critical metadata locally for the longest credible outage; a 24-hour buffer is a reasonable pilot baseline where storage permits.	Verify clock alignment and sensor continuity before backfilling data.
Layer 2 – Edge / gateway	Performs filtering, local rules, video inference, compression and forwarding.	Run the last validated model/rule set locally; prioritise life-safety events over routine telemetry; use store-and-forward queues.	Replay queued events in sequence, suppress duplicates and preserve original timestamps.
Layer 3 – Analytics / integration	Cross-system analytics, trend detection and multi-project learning.	Cloud-only analytics pause. No automatic model update or rule change is permitted while disconnected.	Synchronise data, run integrity checks, then resume analytics/model-management workflows.
Layer 4 – Decision / HMI	Central dashboard, mobile alerts and integrated escalation.	Use local control-room HMI, radio/SMS/local-network alerts, and pre-defined manual escalation. If digital PTW becomes unavailable, revert to the approved manual contingency process.	Reconcile manual actions and close-outs against the restored digital record.
Layer 5 – Assurance / learning	Central audit trail, governance reporting and learning analytics.	Preserve immutable local logs and supervisor decisions; defer non-critical reporting.	Reconcile gaps, document outage duration, verify missed/duplicate events, and complete post-outage assurance review.

J. Technology as an enabler, not a substitute

The framework's central socio-technical claim is that technology operates on, and depends upon, people, organisation, and work design.

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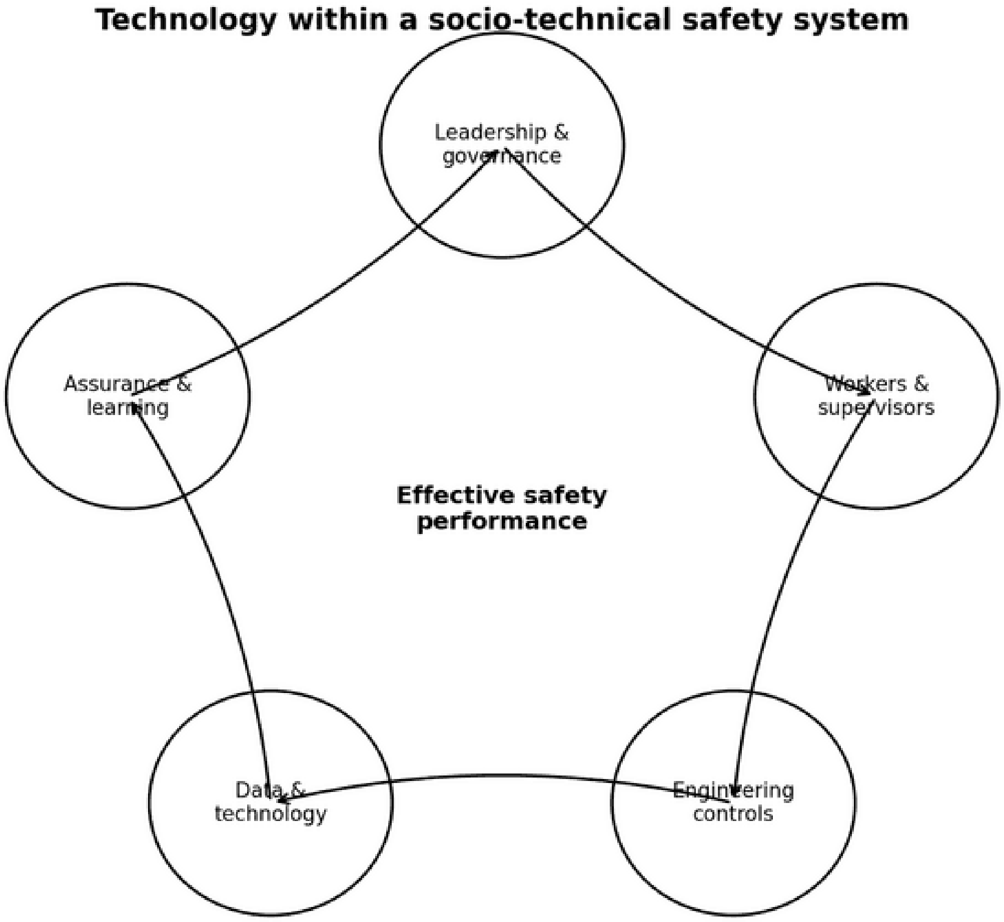

Figure 13. Technology positioned as one component within a socio-technical safety system.

Evidence for this position is direct. Worker acceptance and support structures formed one of three factors determining wearable adoption in Saudi construction, alongside technical and adoption barriers (Mosly, 2026). Workers in a real-workplace exoskeleton trial responded individually and inconsistently to the same device (Bennett et al., 2023). Stakeholder research on exoskeletons recorded uncertainty about practical value, usability, and safety impact (Kim et al., 2019). Digital-twin research records change management and cultural shift as a key adoption challenge (Manzoor et al., 2026). And safety-climate and machine-learning studies converge on supervision, management commitment, crew stability, and leadership development as dominant predictors of serious injury exposure (Erkal et al., 2023; Makki & Mosly, 2021). Technology amplifies organisational capability; it does not create it.

VI. OPERATIONALISING THE FRAMEWORK

A. Dimension-to-action matrix

TABLE IV. DIMENSION-TO-ACTION MATRIX

Dimension	Core question	Example controls	Example evidence
Governance & assurance	Are critical risks clearly owned and independently verified?	Standards, assurance plans, contractor governance, escalation	Control-verification records; audit quality; repeat findings

Dimension	Core question	Example controls	Example evidence
Predictive risk intelligence	Can the system detect increasing risk before an event?	Leading indicators, dynamic risk map, thresholds, trend analytics	Permit-interface map; action ageing; high-risk trend alerts
Occupational health	Are cumulative exposures identified and controlled?	Exposure groups, monitoring, health surveillance, heat/fatigue controls	Exposure results; exceedance trends; control effectiveness
Human capability & voice	Can people recognise risk, act, and challenge safely?	Competency, coaching, multilingual communication, stop work	Field verification; worker feedback closure; competency evidence
Digital safety	Does technology improve control reliability without creating new unmanaged risk?	IoT, wearables, geofencing, digital PTW, AI support	Accuracy tests; alarm response; privacy assessment; uptime
PtD & lifecycle safety	Is risk eliminated or reduced before work begins?	Design reviews, BIM, permanent access, lifting/isolation provisions	Design risk closure; constructability reviews; lifecycle hazard register
Resilience & readiness	Can the system adapt to change and recover effectively?	MOC, emergency drills, learning reviews, backup capability	Drill performance; lesson closure; MOC quality; weak-signal trends

B. Proposed maturity model

For pilot purposes, each dimension can be rated on a five-level maturity scale. The scale is intentionally simple and should be validated before formal benchmarking.

- Level 0 – Reactive: Controls mainly respond to incidents; data are fragmented; health exposure is mostly task-specific.
- Level 1 – Defined: Minimum standards, roles, and basic reporting are documented; critical risks are identified.
- Level 2 – Consistent: Controls are applied consistently; leading indicators and contractor assurance are functioning.
- Level 3 – Integrated: Safety, occupational health, design, and operational data are connected; interface risk is actively managed.
- Level 4 – Predictive / adaptive: The organisation anticipates changing risk, validates control effectiveness, learns rapidly, and adapts using reliable data.

An illustrative, non-validated maturity percentage can be calculated as: SV2030-OSTF maturity (%) = [sum of seven dimension ratings / 28] × 100. Each of the seven dimensions is rated from Level 0 to Level 4; therefore, the maximum attainable score is $7 \times 4 = 28$. Equal weighting is recommended only for initial pilots, because the evidence does not yet justify differential national weights. Any future weighting should be derived through expert consensus and empirical validation.

C. Indicator architecture

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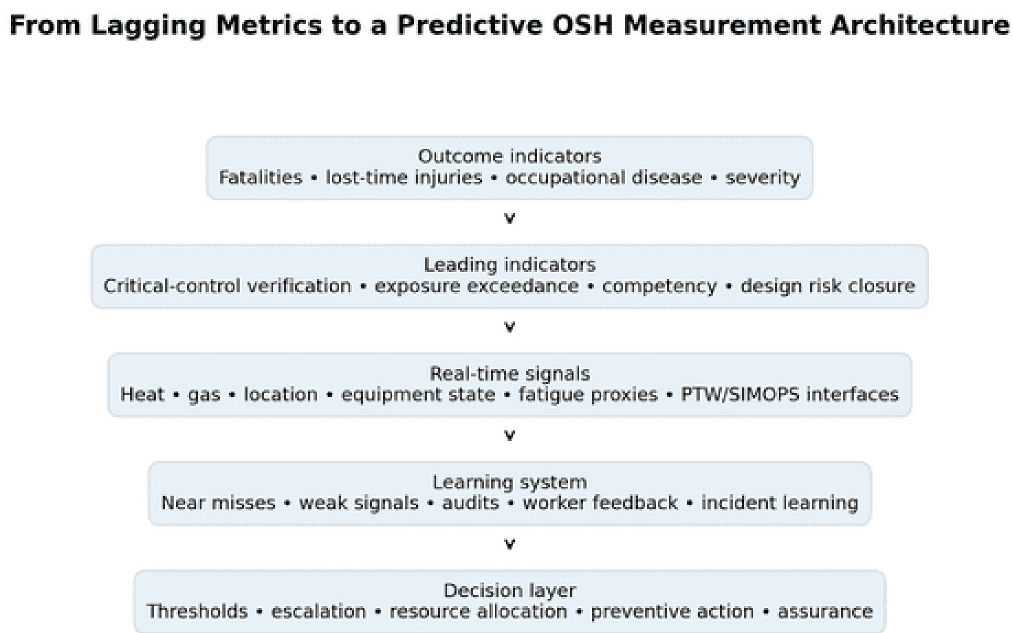

Figure 14. Progression from lagging outcome indicators to predictive and resilience-based measurement.

TABLE V. INDICATOR ARCHITECTURE

Indicator family	Example KPI	Why it matters	Caution
Outcome	Serious injury/fatality; severity; occupational-disease cases	Shows realised harm	Low frequency can hide deteriorating risk
Critical controls	% of high-risk controls independently verified effective	Measures prevention at the hazard barrier	Verification quality matters more than count
Exposure	% exposure samples above action level; heat-alert duration	Makes chronic health risk visible	Requires reliable sampling strategy
Capability	% safety-critical roles competency-verified	Links qualification to demonstrated capability	Avoid attendance-only measures
Design	% significant design risks eliminated/reduced before construction	Moves risk upstream	Requires designer-constructor collaboration
Worker voice	Median time to close worker-raised safety concerns	Tests responsiveness and trust	Fast closure is insufficient if solution quality is poor
Learning	Repeat-event rate; lesson implementation effectiveness	Measures organisational learning	Avoid counting lessons without checking adoption
Digital	Alarm precision/recall or verified usefulness; system uptime	Tests whether digital tools add value	Avoid vanity metrics such as number of sensors installed

D. Technology use-case gate

Because digital safety investment frequently precedes problem definition, the framework specifies a gate that every proposed technology must pass before scaling. The gate reflects documented failure modes: unused or underused devices (Mosly, 2026), privacy and security exposure (Okonkwo et al., 2024), alert fatigue and surveillance concerns (Mohammed et al., 2025), implementation cost and interoperability barriers (Manzoor et al., 2026), and inconsistent worker response to assistive devices (Bennett et al., 2023). For Saudi projects, the gate should also require an environmental robustness test, a degraded-connectivity test, an alert-load test, and a subcontractor-access test before a technology is approved for scale-up.

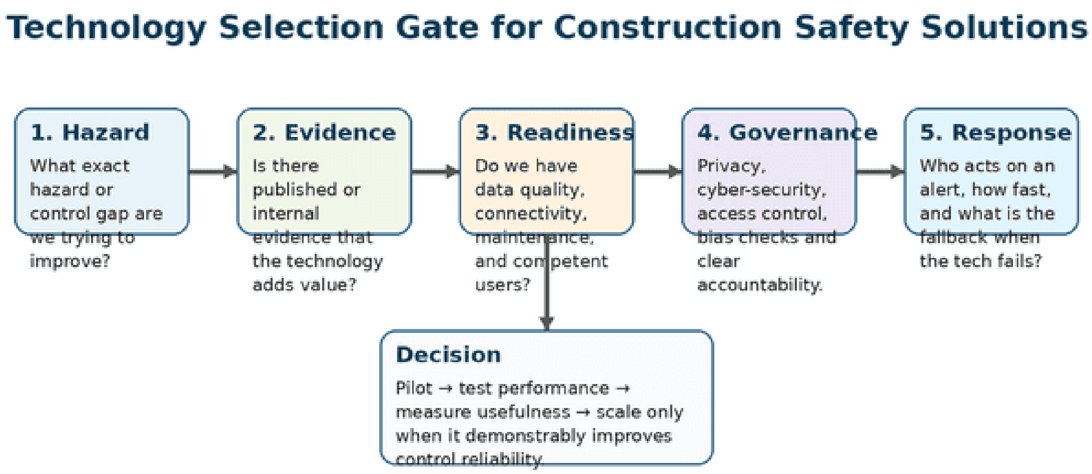

Figure 15. Technology use-case gate for proportionate and purposeful safety-technology adoption.

The gate has five practical consequences. First, no device is procured without a named hazard and a named control it is intended to strengthen. Second, data-minimisation and legal-basis questions are answered before field trial. Third, every alert is mapped to a role with authority and resources to respond. Fourth, accuracy and benefit are measured against pre-agreed criteria rather than vendor benchmarks. Fifth, scaled deployments retain periodic review and a documented fallback when the technology fails.

E. Interoperability and data standards

Data fragmentation was the most severe operational deficit in the practitioner survey, with data continuity scoring lowest of all constructs at 3.77 out of 5.0 (Abdul Salam, unpublished practitioner survey), and interoperability appears as the first of five challenges in blockchain–digital twin research (Manzoor et al., 2026). Four minimum standards therefore apply across the framework:

• Common definitions. A single agreed taxonomy for incidents, near misses, exposures, critical controls, and corrective actions, shared between owner, contractor, and subcontractor.

• Agent-specific exposure records. Exposure data remain hazard-specific, preserving distinct measurement systems, limits, and interpretation rather than being aggregated (Abdul Salam, n.d.).

• Traceable provenance. Every automated alert and analytical output records its source, timestamp, and processing path, so that decisions can be audited and models retrained on trustworthy data (Manzoor et al., 2026).

• Portable worker-level records. Exposure and competency histories follow the worker across tasks, contractors, and projects, using a Worker Exposure Profile structure that integrates monitoring data, surveillance records, and task history to support risk-based decisions, job rotation, and early intervention (Abdul Salam, unpublished practitioner evidence).

1) Short-duration Tier-2/Tier-3 subcontractor integration

Digital maturity should not become a barrier to controlling short-duration subcontractors. For Tier-2/Tier-3 firms mobilised for approximately 30–90 days, the principal contractor or client should provide a minimum digital onboarding layer rather than requiring each subcontractor to build its own technology stack. The objective is to achieve traceability, least-privilege access, and consistent control verification with the lowest practical integration burden.

TABLE VI. MINIMUM DIGITAL-GOVERNANCE PROTOCOL FOR SHORT-DURATION SUBCONTRACTORS

Lifecycle stage	Minimum requirement	Low-infrastructure fallback
Pre-mobilisation	Create a time-bounded digital identity linked to the sponsoring contractor, work package, role and competency record; define what data are collected and why.	Client/prime-contractor onboarding kiosk or supervisor-assisted registration; no proprietary subcontractor platform required.
Access / permissions	Role-based least-privilege access only to relevant permits, zones, inspections and actions; account expiry tied to demobilisation date.	QR/badge/RFID identity with browser-based or shared-device access.
Operational data	At minimum capture PTW participation, safety-critical competency status, critical-control verification, high-risk alerts and unresolved actions.	Supervisor gateway or offline form caches data for later synchronisation.
Privacy / health data	Provide worker notice; prohibit secondary use of location/health data; collect only data necessary for the stated safety purpose.	Use pseudonymous worker IDs where individual identity is not required for the safety decision.
Assurance	The sponsoring Tier-1 contractor remains accountable for data completeness, alert response and close-out quality for the subcontractor.	Daily reconciliation sheet / controlled upload when live integration is unavailable.
Demobilisation	Revoke access immediately at demobilisation; transfer open actions to the sponsoring contractor; retain records only under the project/legal retention schedule.	Confirm device return, credential closure and local-cache upload before final release.

This protocol prevents a common governance failure in which digitally mature owners receive rich data from major contractors while short-term subcontractors remain effectively invisible. The framework therefore treats subcontractor integration as a sponsorship responsibility: the higher-tier organisation must provide the interface, verify data quality, and ensure that workers are not excluded from critical safety controls because their employer lacks infrastructure.

F. A note on analytics methods and interpretability

The framework's predictive ambition should be matched by methodological discipline. Reported prediction accuracies range widely across the literature: classical ensemble methods on Saudi incident data reached 89% accuracy for severity classification (Alsulamy et al., 2026); a study classifying 1,963 OSHA incidents in the southeastern United States found random forest and decision trees most accurate, with age, height, occupation, and event

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type as significant predictors (Oladele et al., 2025); and an LLM-based classifier reported 94.5% accuracy with 98.9% recall against XGBoost's 97.9% accuracy and 97.5% recall (Park et al., 2026). These figures are not directly comparable, because they differ in outcome variable, dataset, class balance, and validation method. Two lessons follow: benchmark models on the organisation's own data before operational use, and prefer models whose reasoning can be inspected and explained to supervisors and workers, since an unexplainable alert is unlikely to change field behaviour (Mohammed et al., 2025).

VII. ILLUSTRATIVE 2026–2030 ROADMAP

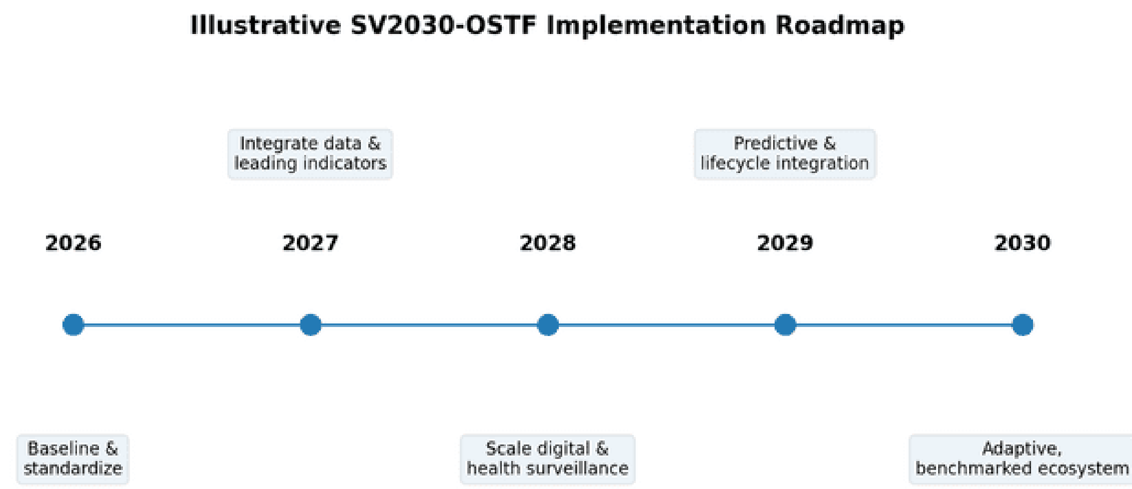

Figure 16. Staged roadmap for organisations piloting the SV2030-OSTF.

2026 – Baseline and standardise. Establish common critical-risk definitions, exposure inventories, contractor expectations, incident taxonomy, role-based competency requirements, and a baseline maturity assessment. Complete a technology inventory and apply the use-case gate retrospectively to existing deployments. Publish the data-governance rulebook before any expanded sensing is introduced.

2027 – Integrate leading indicators. Link permits, critical-control verification, action tracking, exposure monitoring, and contractor assurance into a common dashboard. Begin dynamic interface-risk mapping for high-risk work. Pilot computer-vision compliance checking on a single high-value scope with a defined accuracy threshold and a human verification step (Mohy et al., 2025). Introduce a Worker Exposure Profile for one high-exposure trade group.

2028 – Scale occupational health and digital safety. Expand heat and exposure sensing, targeted wearables, and connected equipment where use cases are proven. Formalise privacy and cybersecurity controls and complete a privacy impact assessment covering location and physiological data (Okonkwo et al., 2024). Introduce longitudinal exposure profiles for selected high-risk groups. Deploy XR training and assessment for defined high-risk tasks with scheduled retention testing (Scorgie et al., 2023). Evaluate exoskeletons in defined high-exertion tasks using a field-based trial protocol (Bennett et al., 2023).

2029 – Predictive and lifecycle integration. Connect planning, design, BIM/digital-twin data, operational alarms, and work execution. Pilot predictive models for selected hazards with human oversight and documented performance testing, benchmarked against the organisation's own incident and observation data. Extend digital twin use to safe design and planning, risk monitoring, and performance improvement across the lifecycle (Teizer et al., 2022). Establish independent verification of automated alerts.

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2030 – Adaptive, benchmarked ecosystem. Use validated maturity and performance indicators to compare improvement over time, strengthen cross-project learning, and focus resources on areas where leading signals reveal persistent risk. Formalise cross-contractor data portability, cyber-resilience testing, and periodic revalidation of every deployed model and device.

VIII. APPLICATION TO HIGH-RISK SAUDI WORK ENVIRONMENTS

TABLE VII. APPLICATION TO HIGH-RISK SAUDI WORK ENVIRONMENTS

Environment	Illustrative SV2030-OSTF applications
Construction and mega-projects	Daily permit-interaction maps; lifting/traffic geofencing; scaffold/fall critical-control verification; heat-risk integration; contractor maturity scoring
Industrial and brownfield work	Dynamic SIMOPS assessment; isolation-state verification; gas and atmospheric monitoring; management of change; 24/7 shift readiness and handover assurance
Logistics and warehousing	Vehicle-pedestrian separation; telematics; fatigue and shift analysis; loading/unloading critical controls; automated proximity alerts
Utilities and public works	Excavation interface control; underground-service detection; confined-space monitoring; electrical authorisation and temporary-power assurance
Operations and maintenance	Lifecycle design reviews; permanent access and anchorage; condition-based maintenance risk; exposure histories; emergency and outage readiness

Applied more fully, each environment activates the framework differently. In construction and mega-projects, the dominant risk mechanism is interface density under schedule pressure, so the priority capabilities are permit-driven interface mapping, computer-vision verification of fall and PPE critical controls, and heat-integrated work-rest scheduling; the evidence base here is the strongest, with documented deep-learning detection of workers, PPE, and plant from site imagery (Alateeq et al., 2023; Mohy et al., 2024, 2025) and UAV–BIM integration for hazard identification (Akinsemoyin et al., 2024; Alizadehsalehi et al., 2018).

In industrial and brownfield work, the dominant risk mechanism is state change — isolation integrity, simultaneous operations, and live-plant interfaces — where digital twin logic for monitoring, control, and performance improvement is most directly applicable (Shariatfar et al., 2022; Teizer et al., 2022), and where management of change quality is a leading indicator of adaptive capacity.

In logistics and warehousing, the dominant mechanism is kinetic energy between vehicles and pedestrians, and fatigue associated with shift patterns; proximity alerting, telematics, and fatigue analysis dominate, though this sector has thinner construction-specific digital-safety evidence and should be treated as an extension programme rather than a validated application.

In utilities and public works, the dominant mechanism is incomplete knowledge of existing underground and electrical infrastructure, which favours digital survey and permit integration over wearable-led approaches, together with the automated hazard identification during design and construction that BIM-based frameworks support (Balgheeth, 2016).

In operations and maintenance, the dominant mechanism is cumulative exposure and access to assets for inspection, cleaning, and replacement; this is where Prevention through Design decisions have the longest consequences and where Worker Exposure Profile continuity delivers the greatest preventive value across a long service life (Abdul Salam, unpublished practitioner evidence).

IX. DISCUSSION

The central proposition of this paper is that Vision 2030 creates both a need and an opportunity for OSH to evolve from a largely event-driven management function into an integrated operating capability. This does not imply that compliance, inspection, or incident investigation become less important. Rather, they become part of a broader system that also monitors exposure, verifies control effectiveness, learns from variability, and uses data to anticipate risk.

A second proposition is that occupational health must become more visible within mainstream safety performance. Construction and industrial organisations can report low injury frequencies while their workers still experience significant noise, heat, dust, chemical, ergonomic, or fatigue exposures. Global burden estimates attribute substantial disability-adjusted life years and premature mortality to workplace risk factors, with disease accounting for a large share of the total (Abdul Salam, n.d.), and practitioner surveys rank welding fumes, silica, and noise as priority exposures while simultaneously identifying management priority and record continuity as the binding constraints on managing them (Abdul Salam, unpublished practitioner survey). A transformed OSH system therefore requires health indicators capable of influencing daily operational decisions, not merely annual medical statistics.

Third, the framework treats digitalisation cautiously but specifically. The evidence for computer vision, wearables, digital twins, and predictive analytics is now substantive: detection models recognise PPE and plant with high reported accuracy (Alateeq et al., 2023; Mohy et al., 2024, 2025); digital twin applications span monitoring, prediction, simulation, decision support, and training (Luo et al., 2024); and machine learning predicts incident characteristics well above baseline (Alsulamy et al., 2026; Tixier et al., 2016). Yet the same literature documents dataset scarcity, occlusion and illumination limitations, computational constraints, data-quality anomalies, model generalisation problems, alert fatigue, and surveillance concerns (Mohammed et al., 2025; Mohy et al., 2025), together with interoperability, cost, privacy, and change-management barriers (Manzoor et al., 2026). Technology should therefore be deployed only where a defined hazard-control problem exists and where the organisation can demonstrate a reliable human response to the information generated.

Fourth, the framework extends responsibility upstream through Prevention through Design. This is strategically important for a country creating new infrastructure at scale. The safest temporary control is often less effective than eliminating the hazard through layout, access, isolation, modularisation, or permanent engineered features. Framing the digital twin as beginning with safe design and planning, rather than with site sensing, operationalises this priority (Teizer et al., 2022).

Fifth, the framework emphasises resilience, because high-risk work is rarely performed exactly as imagined in a procedure. Weather changes, equipment becomes unavailable, interfaces emerge, and operational states shift. Organisations therefore need the capability to detect when assumptions are no longer valid and to adapt without normalising uncontrolled risk — the capacities to respond, monitor, learn, and anticipate (Hollnagel, 2018).

Sixth, the human evidence consistently outranks the technological evidence. Supervisory experience with the crew, crew stability, supervisory span, and frontline leadership development maturity were the strongest predictors of serious injury and fatality exposure in one study (Erkal et al., 2023); supervision, management commitment, and safety justice dominate Saudi safety-climate prediction (Makki & Mosly, 2021); and worker acceptance structures were one of three determining factors in Saudi wearable adoption (Mosly, 2026). Any technology programme that degrades supervisory presence — for example, by substituting dashboards for field engagement — removes the strongest protective factor identified in the literature.

The additional edge-case controls are important because the digital layer can itself become a source of risk if the system performs well only under ideal weather, depends on continuous connectivity, floods supervisors with non-actionable alerts, or excludes short-term subcontractors. The revised framework therefore defines environmental validity, alert triage, offline continuity, and subcontractor onboarding as operational assurance requirements rather than optional IT considerations.

A. Relationship to existing Saudi OSH initiatives

SV2030-OSTF is intended to complement, not replace, national OSH governance. Its dimensions map naturally to the National Strategic Program themes of awareness, capability, regulation, inspection, and reporting, while adding an applied layer for predictive analytics, occupational exposure, design, digital governance, and resilience. The framework could therefore be piloted voluntarily by organisations or researchers as an implementation and research model, without implying any change to existing legal requirements. In the Saudi public-sector construction context, where better enforcement of regulations and laws has been identified as the key driver of improved outcomes, the framework's governance dimension should be read as reinforcing enforcement capability through better evidence rather than substituting for it (Balgheeth, 2016).

B. What would constitute empirical validation?

A future validation study could proceed in three phases. Phase 1 would convene a Delphi panel of Saudi OSH, engineering, occupational-health, regulator/client, and contractor experts to test content validity and refine dimension definitions. Phase 2 would pilot the maturity instrument across multiple organisations or projects and examine inter-rater reliability, internal consistency where appropriate, and relationships with established leading and lagging indicators. Phase 3 would assess predictive validity longitudinally, to determine whether higher maturity, or specific dimensions, are associated with improved control reliability, lower exposure exceedance, and better safety outcomes.

Technology-specific validation should accompany this. Detection models require local site validation against occlusion, PPE variants, illumination, and dust before operational reliance (Mohy et al., 2025). Predictive models require temporal hold-out testing on local data before deployment, following the practice of validating against held-back datasets (Park et al., 2026). Assistive devices require field trials with experienced workers rather than laboratory participants, since usability judgements differ materially between the two (Bennett et al., 2023). XR training requires retention measurement at defined intervals rather than immediate post-testing, given that only a minority of published studies report retention data (Scorgie et al., 2023).

Until such validation is completed, the framework should be treated as a structured decision-support model rather than a certified score, regulatory standard, or evidence of safety performance.

X. LIMITATIONS

This study is conceptual and includes no primary empirical data. The proposed seven dimensions reflect a synthesis of available evidence and policy context, but they have not yet been validated through expert consensus or multi-site testing.

The literature base intentionally prioritises Saudi and construction/high-hazard research, which may limit direct applicability to lower-risk service sectors. Future work should test sector-specific adaptations, particularly for logistics, healthcare, and office-based work where the hazard profile and technology mix differ substantially.

The maturity formula is illustrative. Equal weighting is a neutral starting point for pilots, not a validated representation of relative importance. Future weighting should be evidence-based.

The technology evidence reviewed here is uneven in quality. Reported detection accuracies vary with dataset, class balance, and validation design; several of the studies cited are recent or have low citation counts; and the digital-twin literature itself concludes that application remains at an early stage and is not yet streamlined in practice (Hou et al., 2020; Luo et al., 2024). Framework claims about predictive capability should therefore be read as directional rather than established.

Digital-safety technologies evolve quickly. Specific devices, analytics, and implementation barriers described in the current literature may change before 2030, so the framework focuses on governance

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principles and capability rather than on any specific vendor or technology.

The exposure survey data reported are drawn from a practitioner sample of 65 respondents in oil and gas, infrastructure, and urban development, and therefore represent professional judgement rather than measured exposure or employment-population inference. The figures are reported as recorded and should not be extrapolated beyond comparable populations.

Finally, exoskeleton and wearable evidence base effects on injury outcomes remains thin: field trials are small, worker responses are heterogeneous, and stakeholder research records continuing uncertainty about practical value and safety impact (Bennett et al., 2023; Kim et al., 2019). The framework accordingly treats these as evaluated controls rather than established solutions.

XI. FUTURE RESEARCH AGENDA

- Validate the seven dimensions through a Saudi multi-stakeholder Delphi study.
- Develop a standardised SV2030-OSTF assessment questionnaire with behavioural anchors for each maturity level.
- Test the relationship between maturity scores and serious-injury precursors, critical-control reliability, and occupational-exposure outcomes.
- Develop Saudi-specific dynamic heat-risk models incorporating workload, PPE, acclimatisation, duration, and recovery.
- Evaluate the accuracy, usability, privacy impacts, and cost-effectiveness of wearables and connected safety devices under Saudi climatic and working conditions.
- Create permit-driven SIMOPS interaction models that integrate spatial, temporal, and operational-state data.
- Examine how Prevention through Design can be embedded into BIM, digital twins, and asset handover requirements for major infrastructure.
- Establish methods for ethical worker-level exposure histories that support prevention without creating inappropriate surveillance.
- Benchmark computer-vision hazard-detection models on Saudi site conditions, reporting precision, recall, and false-alarm rates rather than headline accuracy alone.
- Compare machine-learning and large-language-model approaches to incident prediction on Saudi datasets, with explicit attention to interpretability and supervisory usability.
- Evaluate XR training against field-verified competency outcomes with scheduled retention intervals, addressing the identified gaps in theoretical grounding and long-term retention measurement (Dodoo et al., 2025; Scorgie et al., 2023).
- Conduct field-based trials of exoskeletons and assistive robotics in Saudi high-exertion trades, measuring task time, posture, physiological load, and worker acceptance (Bennett et al., 2023).
- Investigate the minimum interoperability standard required for cross-contractor exposure and competency data portability, and test whether blockchain or other trust mechanisms add measurable value over conventional governance.
- Examine the interaction between automated alerting and supervisory field presence, to confirm that digital safety does not displace the strongest identified protective factors.
- Assess the cybersecurity and cyber-resilience of connected safety systems in live industrial environments, where sensor or dashboard failure constitutes a new operational hazard.

XII. CONCLUSION

Saudi Vision 2030 provides a powerful context for rethinking occupational health and safety as an enabling capability for productive, attractive, and sustainable work. The proposed SV2030-OSTF translates this opportunity into seven operational dimensions: governance and assurance; predictive risk intelligence; occupational health and exposure prevention; human capability, leadership, and worker voice; digital safety and connected worksites; Prevention through Design and lifecycle safety; and resilience, learning, and readiness. The framework's central principle is integration. Safety outcomes improve most credibly when technology, leadership, health protection, design, data, and worker participation reinforce one another — a position supported by two independent strands of evidence, in which organisational and supervisory variables dominate prediction of serious injury exposure (Erkal et al., 2023), and in which digital tools fail or stall when adoption, interoperability, privacy, and trust conditions are unmet (Manzoor et al., 2026; Mosly, 2026). The framework further specifies a technology use-case gate and a five-layer safety intelligence architecture so that digital investment is tied to defined hazard-control problems and governed by documentation, validation, and human response. The model is deliberately presented as a research framework rather than a validated national standard. Its next step is empirical testing across representative Saudi sectors and projects. If validated, it could provide a common language for measuring progress from reactive compliance toward predictive, health-inclusive, and resilient OSH performance by 2030.

DECLARATIONS

Funding: No external funding was received for this study.

Conflict of interest: The author declares no known conflict of interest.

Ethics approval: No new human-subject data were collected for this conceptual paper. Aggregated results from a related de-identified practitioner survey are cited as secondary evidence; the originating study documentation should be provided separately if requested by the target journal.

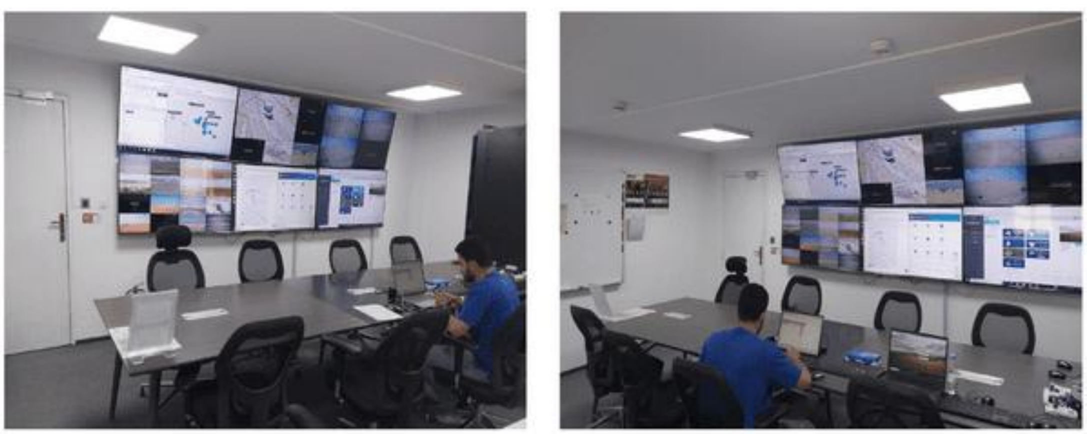
Data availability: No new dataset was generated to derive or validate the conceptual framework. Public sources are identified in the reference list. Aggregated statistics from the author's related de-identified practitioner survey (N = 65) are reproduced only as contextual evidence; anonymised summary data are available from the author on reasonable request and can be deposited in a recognised repository if required by the journal.

Author contribution: The author developed the concept, synthesised the literature, designed the proposed framework, and prepared the manuscript.

APPENDIX A

Practice-Based Digital Safety Illustrations

The following images are included as implementation illustrations from the author-provided evidence pack and video. They demonstrate the practical feasibility of control-room monitoring, environmental sensing, automated reporting, standards retrieval, and video-enabled field monitoring. They are not treated as independent empirical validation of the SV2030-OSTF.



SECC Safety & Environmental Command Control room Pioneer camp(May 2024 to Present)

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Figure A1. Safety & Environmental Command Control Room practice illustration.

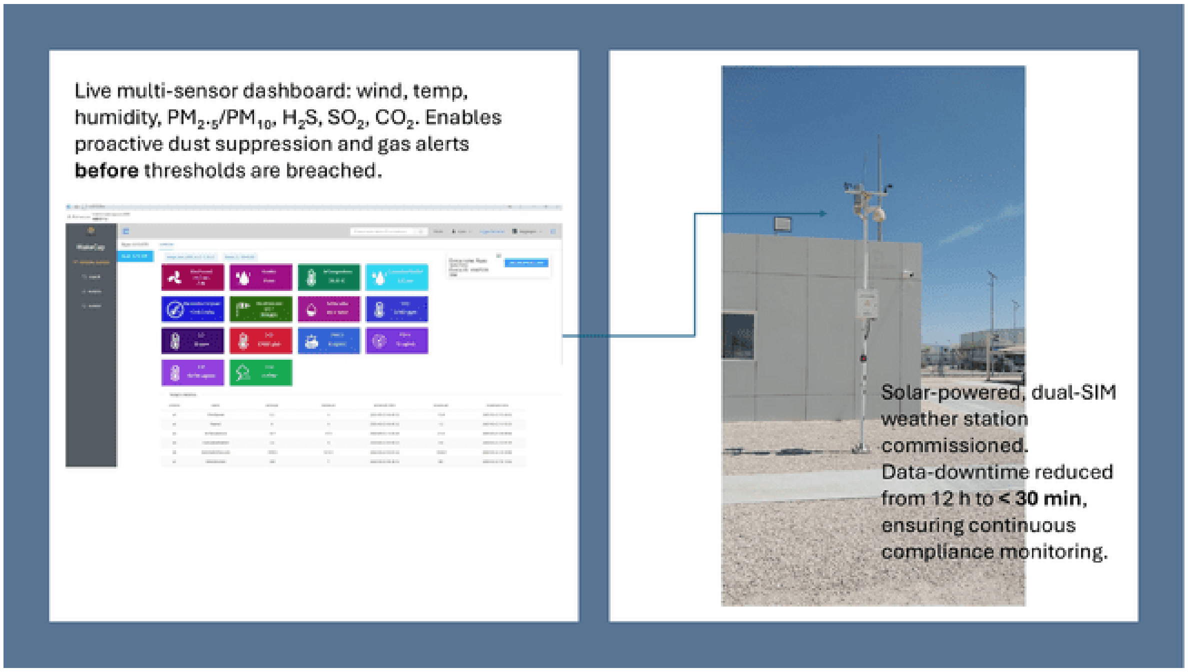

Figure A2. Live multi-sensor environmental dashboard and weather-station practice illustration.

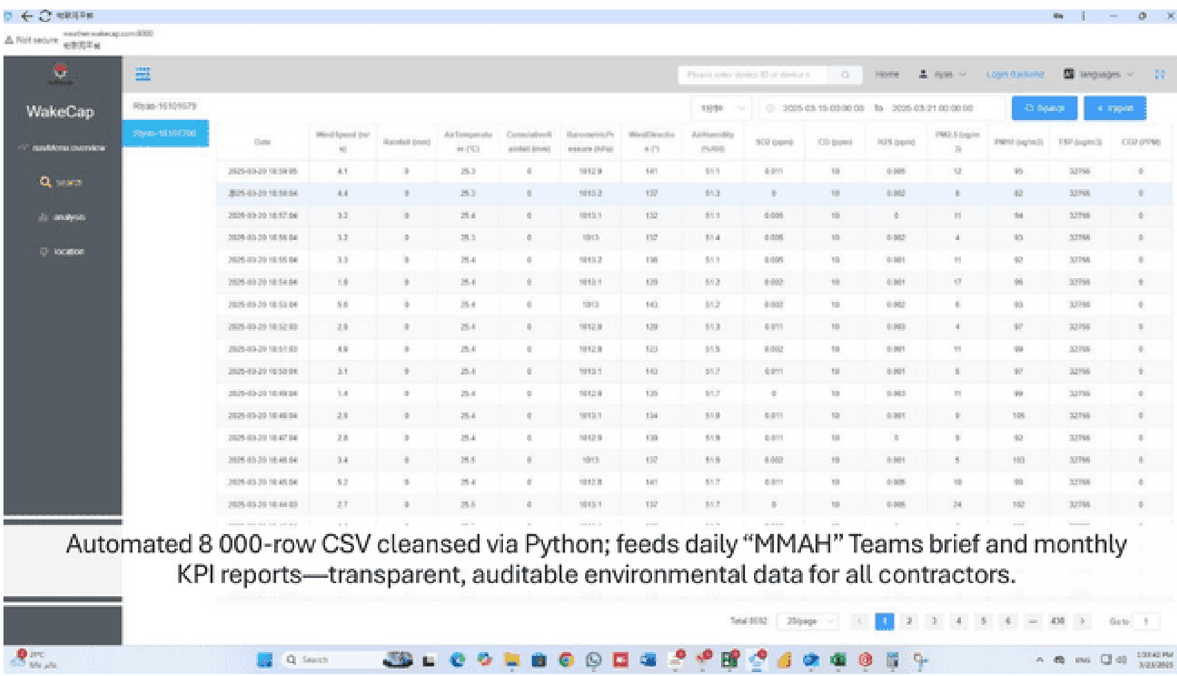

Figure A3. Automated environmental data processing and KPI reporting practice illustration.

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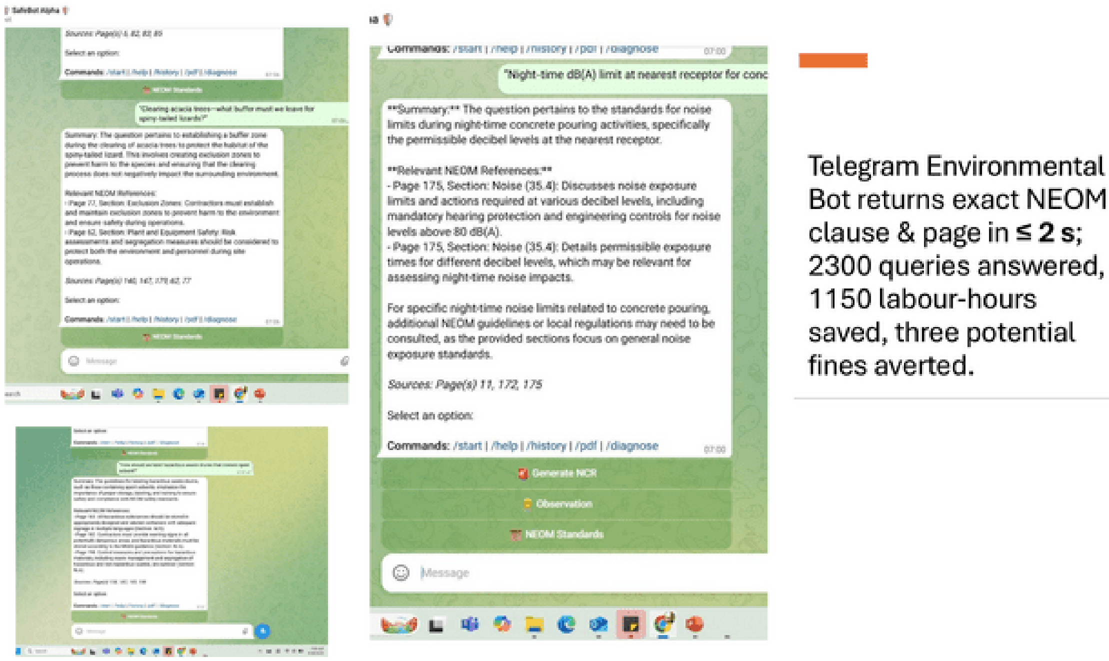

Figure A4. Standards-retrieval bot practice illustration.

Figure A5. Contact sheet from the submitted field-monitoring video.

Figure A6. Selected video frame illustrating the potential input stream for computer-vision safety analytics.

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