

Digital Transformation of Construction Site Safety Management: Technologies, Framework, and Practices

Rui Li

Zibo Polytechnic University, Zibo, Shandong, China

Abstract: Construction sites remain among the most hazardous working environments, with falls, struck-by incidents, and equipment-related accidents causing persistent casualties worldwide. Conventional safety management relies heavily on manual inspection, paper-based records, and reactive correction, which limits timely hazard detection and weakens preventive capacity. This paper examines the digital transformation of construction site safety management through the integration of building information modelling, Internet of Things sensing, computer vision, and digital twin platforms. It reviews how these technologies shift site safety from after-the-event response to continuous, data-driven prevention. A four-layer implementation framework is proposed, covering data acquisition, transmission, analytics, and decision support, and is illustrated with representative applications such as automated personal protective equipment compliance checking and real-time hazard zone monitoring. The analysis shows that digital safety systems improve hazard identification accuracy, shorten warning latency, and support evidence-based supervision, while challenges related to data interoperability, deployment cost, and worker acceptance require structured safeguards. The study contributes a practical roadmap for contractors seeking to upgrade safety governance with measurable, scalable digital tools.

Keywords: Digital Transformation; Construction Safety; Building Information Modelling; Internet of Things; Computer Vision; Safety Management

1. Introduction

Construction activity forms the backbone of economic development yet consistently ranks among the most dangerous industries. Global

statistics show elevated rates of fatalities and severe injuries, with falls from height, struck-by objects, and unsafe equipment operation accounting for a large share of incidents on building and civil engineering sites [1]. In many projects, safety supervision still depends on periodic site walks, handwritten checklists, and post-incident investigation, leaving a gap between hazard emergence and corrective action [2]. The persistence of these patterns indicates that technical capability, rather than awareness alone, is the missing element in safer delivery.

Scholars have argued that the fragmentation of traditional safety processes prevents early identification of design-stage risks and weakens coordination among contractors, supervisors, and workers [3]. Building information modelling has been applied to visualize safety standards and embed preventive measures during planning, while sensing and vision technologies have shown strong potential in automating compliance monitoring that was previously labor intensive [4,6]. Together, these advances support a transition from inspection after harm to prevention before exposure.

This paper investigates how digital transformation reshapes construction site safety management. It synthesizes the enabling technologies, proposes a layered implementation framework, and discusses the benefits and remaining barriers. The remainder is organized as follows: Section 2 reviews conventional practice and its limitations; Section 3 examines the core digital technologies; Section 4 presents the implementation framework; Section 5 analyzes benefits, challenges, and safeguards; Section 6 concludes with practical implications.

2. Conventional Site Safety Management and Its Limitations

2.1 Reactive Rather Than Preventive

Traditional safety management is predominantly reactive. Inspections occur at fixed intervals, and hazards are usually corrected after they are

observed, which means workers may already be exposed to risk during the interval between checks [2]. The absence of a continuous data flow makes it difficult for project managers to prioritize the most dangerous activities in real time, and corrective actions often arrive too late to prevent the first occurrence of an incident.

Beyond the human cost, weak safety control imposes a measurable economic burden. Project delays, higher insurance premiums, and legal liability after an incident can exceed the cost of preventive investment by a wide margin. Regulators in several jurisdictions have tightened documentation duties, requiring firms to keep traceable safety records that paper systems cannot supply efficiently [2]. This external pressure, combined with client demand for demonstrable performance, accelerates interest in digital alternatives that produce evidence by design rather than by retrospective effort.

2.2 Fragmented Information Flow

Safety records are often scattered across spreadsheets, paper forms, and separate software systems owned by different parties. This fragmentation hinders the aggregation of lessons learned and slows the feedback loop that could improve subsequent tasks [3]. Without a shared data environment, the same hazard may recur on different floors or shifts, and supervisors lack a single view of cumulative risk across the project. Integrated digital platforms resolve this by storing safety events in one structured repository where trends can be queried and compared across shifts, crews, and contract packages. When the same near-miss recurs, the system surfaces it instead of hiding it inside a forgotten form, enabling targeted intervention before a serious injury occurs [3].

2.3 Limited Visibility of High-Risk Operations

High-risk operations such as working at height, heavy lifting, and confined-space entry are difficult to monitor continuously with manual methods. Supervisors cannot be present at every location simultaneously, and visual inspection alone misses subtle indicators such as proximity to hazard zones or fatigue-related behavior [5]. These blind spots motivate the adoption of automated monitoring that does not depend on human attention at all moments.

Digital monitoring addresses this by extending

supervisory reach beyond line of sight. Wearable tags and fixed sensors together cover spaces that a walking inspector cannot occupy simultaneously, and analytics translate the raw stream into a small set of prioritized warnings. The result is broader coverage with lower dependence on chance observation [5,10].

3. Core Technologies Enabling the Transformation

3.1 Building Information Modelling for Design-Stage Prevention

Building information modelling supports prevention through design by simulating construction sequences and flagging fall hazards before work begins [1]. Practitioners have built systems that store safety clauses and visualize required protective measures directly in the design environment, improving awareness among workers and supervisors [3]. Studies also demonstrate that most fall-related hazards can be identified and mitigated at the design stage through embedded checking rules, which reduces the burden placed on site correction [5]. The value of building information modelling reaches beyond static rule checking. By linking the model to the construction schedule, four-dimensional simulation shows how the site evolves week by week and where temporary structures, access routes, and protected zones conflict [1,5]. Planners can test alternative sequences and choose the arrangement that minimizes worker exposure, converting safety from a later constraint into a design variable considered alongside cost and time from the earliest stage.

3.2 Internet of Things and Wearable Sensing

Internet of Things devices, including smart helmets, wristbands, and location beacons, collect physiological and positional data that reveal unsafe postures, falls, and unauthorized entry into restricted zones [4]. Integrated systems can alert both workers and supervisors when protective equipment is not used or when a person approaches a danger area [10]. Such real-time feedback changes safety management from periodic auditing to continuous guarding and creates a verifiable record of on-site behavior.

The richness of sensor data also supports finer analysis than manual observation allows. Continuous position traces reveal patterns of movement that indicate whether exclusion zones

are respected, while physiological signals can flag fatigue before it causes error [4]. At the same time, the collection of personal data raises legitimate privacy questions that contractors must address through clear policy, limited retention, and worker consultation, so that protection of safety does not erode protection of privacy [10].

3.3 Computer Vision for Automated Compliance

Computer vision models based on deep learning detect personal protective equipment such as helmets, vests, and safety shoes directly from site cameras. Comparative studies of You Only Look Once architectures report mean average precision above 0.92 for multi-class protective equipment detection, validating the reliability of automated checking under varied lighting and angles [6]. Custom models trained on site-specific images reach similar accuracy and can issue voice reminders when compliance lapses, turning passive recording into active intervention [9].

3.4 Digital Twin for Integrated Risk Monitoring

A digital twin connects the physical site with a dynamic virtual model, enabling real-time risk monitoring that combines four-dimensional building information modelling with wearable tracking [10]. Literature reviews indicate that digital twin applications in construction safety remain at an early stage but show clear value in real-time warning, risk prediction, and emergency simulation [7]. Exploratory demonstrators further confirm the feasibility of location-enabled twins for health, safety, and progress monitoring within a single operational picture [8].

Table 1. Conventional and Digital Site Safety Management: A Comparison

Dimension	Conventional Mode	Digital Mode
Hazard identification	Manual inspection at fixed intervals	Continuous sensing and model-based checks
Data recording	Paper forms and separate spreadsheets	Unified digital platform
Response speed	Hours to days	Seconds to minutes
Accountability	Individual memory	Auditable automated logs
Risk visibility	Partial, after the event	Real-time, site-wide

Maturity differs across the technologies. Computer vision and Internet of Things solutions are already commercial and operate on familiar site infrastructure, whereas digital twin implementations remain mostly pilot-scale and depend on high-quality models and sensor data [7,8]. This uneven readiness suggests that contractors should sequence investment, beginning with tools that deliver quick, visible wins before attempting organization-wide twin platforms that demand deeper integration.

4. Implementation Framework

4.1 A Four-Layer Architecture

To guide adoption, this paper proposes a four-layer framework: a data acquisition layer composed of sensors, cameras, and building information models; a transmission layer of wireless networks and edge gateways; an analytics layer applying computer vision and rule engines; and a decision-support layer of dashboards and automated alerts. Each layer feeds the next, turning raw signals into actionable safety instructions and closing the loop between observation and intervention.

Beyond the technical stack, the framework assumes a governance layer that defines who receives alerts and how exceptions are handled. Without clear response protocols, even accurate detection produces no safety gain, because no one is authorized to stop work when a warning appears. Contractors should therefore pair the digital pipeline with explicit escalation rules and named owners for each alert class, ensuring that the system changes behavior rather than merely generating data [10].

4.2 Data Acquisition and Transmission

The acquisition layer integrates heterogeneous sources, including location tags, environmental sensors, and site imagery. Edge devices preprocess data on site to reduce latency, while wireless transmission moves consolidated streams to the analytics layer without overloading the network [4,10]. Standardized interfaces are essential so that devices from different vendors can contribute to one coherent safety picture instead of operating as isolated silos.

Transmission reliability is as important as sensor quality. Sites are noisy radio environments where concrete structures and machinery attenuate signals, so edge processing and local

buffering prevent data loss during network interruptions. A resilient pipeline ensures that safety evidence remains complete even when connectivity is temporarily weak [4].

4.3 Analytics and Decision Support

The analytics layer applies detection models and rule-based checks to identify non-compliance and hazard proximity. The decision-support layer presents results through supervisor dashboards and worker-facing warnings, ensuring that identified risks lead to prompt action [6,9]. Table 2 summarizes the primary function of each technology within the proposed framework and the applications through which it delivers value.

The decision-support layer must respect cognitive load. Presenting every raw signal to supervisors creates alarm fatigue, so effective systems rank alerts by severity and consolidate related events into a single actionable item. Threshold tuning, informed by site context, determines whether the platform is trusted or ignored [6,9].

Table 2. Core Digital Technologies and Their Primary Functions

Technology	Primary Function	Representative Application
Building Information Modelling	Design-stage hazard simulation	Fall prevention planning [1,3,5]
Internet of Things sensing	Worker location and condition monitoring	Smart helmet alerts [4,10]
Computer vision	Automated PPE compliance checking	Helmet and vest detection [6,9]
Digital twin	Integrated real-time risk monitoring	Hazard-zone tracking [7,8,10]

5. Benefits, Challenges, and Safeguards

5.1 Observed Benefits

Empirical applications show that digital safety systems raise the accuracy of hazard identification, compress warning latency from hours to seconds, and produce auditable records that strengthen supervisory accountability [6,10]. The shift to continuous monitoring also reduces dependence on individual vigilance and helps standardize practice across crews, so that safety performance becomes less sensitive to the experience of a single inspector.

A representative deployment illustrates the effect. On a mid-rise project, automated helmet and vest detection reviewed live camera feeds across the site and flagged non-compliance within

seconds, compared with the daily cadence of manual checks [6,9]. Over the observation window, recorded near-miss events that previously went unseen entered a corrective workflow, and supervisors reported faster closure of safety items. Although absolute reduction in injuries requires longer study, the compression of the detection-to-action cycle is itself a meaningful protective gain that paper-based routines cannot match.

5.2 Remaining Challenges

Three challenges constrain wider deployment. First, interoperability between proprietary devices and platforms remains weak, limiting the fusion of data from multiple sources [7]. Second, initial investment and maintenance cost discourage small and medium contractors that operate on thin margins. Third, worker acceptance is not guaranteed, as some crews perceive continuous monitoring as intrusive or as a tool for punishment rather than protection [4].

These challenges are not insurmountable, but they are frequently underestimated. Technology alone does not guarantee adoption; the same system viewed as supportive by one crew may be resisted by another if its purpose is poorly communicated. Early engagement of workers in tool selection and rule setting reduces opposition and surfaces practical constraints that designers would otherwise miss [7].

5.3 Safeguards for Responsible Adoption

Responsible adoption requires open interfaces and common data standards to ease integration, phased pilots to control cost, and transparent communication about data use to build trust. Training that frames digital tools as protective rather than punitive improves acceptance and sustains long-term compliance. Procurement and contract terms should reward demonstrable safety outcomes, giving contractors a clear incentive to invest in durable capability.

6. Conclusion

The digital transformation of construction site safety management replaces fragmented, reactive routines with connected, data-driven prevention. Building information modelling, Internet of Things, computer vision, and digital twin technologies together enable earlier hazard detection, faster response, and more accountable supervision. The proposed four-layer framework

offers contractors a structured path from pilot to scale, aligning data acquisition, transmission, analytics, and decision support around a single safety objective. Realizing the full potential depends on addressing interoperability, cost, and human factors through standards, phased investment, and participatory implementation. Future work should quantify safety outcomes across project types and develop lightweight solutions suited to small and medium contractors, so that the benefits of digital safety reach the full spectrum of the construction industry.

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