Digital Approaches for Safer Construction Sites: Insights from Large-Scale Accident Data Analysis

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***Abstract*— Despite existing safety protocols, construction remains one of the most hazardous industries, with thousands of incidents occurring annually. This study analyses 8,300 recorded construction accidents from 2023, classified by date, accident type, injury type, material element, and affected body part. The aim is to extract patterns, assess danger levels, and identify the underlying causes of these incidents. A structured hazard index has been developed to prioritise the most severe and common types of accidents. The study then explores how digital technologies, particularly Digital Twin technologies, could help predict, mitigate, or prevent these incidents. By linking accident typologies to the potential real-time monitoring, simulation, and predictive capabilities of digital twins, the research proposes a roadmap for integrating digital tools into safety planning and operational workflows. Finding results support the targeted implementation of Digital Twins high-risk zones such as scaffolding, heavy machinery operation, and dynamic site environments. This work contributes to both the academic discourse on construction safety and the practical deployment of emerging technologies on-site.**

***Keywords*—Construction Safety, Digital Twin (DT), Internet of Things (IoT), Real-time Monitoring.**

I. Introduction

Construction is consistently ranked among the highest-risk sectors globally, accounting for a substantial proportion of workplace accidents and fatalities. In many cases, traditional safety measures are insufficient to address the dynamic and diverse risks on construction sites. Effective accident control is crucial in the construction industry. Employers are responsible for assessing risks and implementing practical measures to safeguard the health and safety of their workforce. This includes ongoing monitoring and surveillance to identify areas where accidents are most likely to occur [1]. According to Lucy et al. (1999), an accident is defined as an unforeseen and unintended event that disrupts the planned sequence of work, potentially causing injuries, equipment damage, loss of productivity, and delays in operations [2]. Furthermore, the occupational safety and health administration reports that at least 60,000 fatal accidents occur on construction sites worldwide each year [3].

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The fatality rate in construction consistently exceeds the average across all other industries worldwide. Traditional tools for occupational safety management at the engineer's disposal are based on the legislation requirements, technical standards, safety guidelines, investigation reports and accident statistics [4].

The construction industry is known as one of the most high-risk sectors in terms of accidents at work, as well as from an economic standpoint. Accidents are a persistent and almost unavoidable aspect of construction projects worldwide. Usually, when an accident happens, it not only has an economic and time impact, but also involves human lives.

Given this context, numerous theories exist to explain the causes of accidents, which can help identify why an incident occurred. Some perspectives emphasize physical hazards (i.e., unsafe conditions), others highlight human behavior (i.e., actions), while some focus on failures within the management system [5]. The most effective approach is one that integrates all these aspects, as accidents are often complex events involving multiple contributing factors. Therefore, during accident investigations, it is essential to consider all relevant elements, including physical hazards and environmental conditions, that may have played a role [6].

Hamid et al., (2019) stated that fatal construction accidents are generally classified by type in the following sequence: falls from height, being struck by objects, being caught in or between equipment or structures, and electrocution [5]. The occupational safety and health administration reports this same classification in the same order. However, simply identifying these types, such as falls or being struck by objects, does not reveal the underlying causes. These classifications describe how the injury occurred, not why. Each type may stem from a variety of contributing factors.

As Al-Tabtabai (2002) emphasized, preventing construction accidents involves forecasting potential incidents and understanding their likely nature under specific circumstances. Such foresight must be based on a thorough analysis of past accidents [7].

In this study, we analyze a dataset of 8,300 accidents that occurred within a company during 2023 and early 2024. Accidents will be categorized by type, cause, body part affected, and severity. Ultimately, we will assess which types of accidents can be addressed or mitigated through digital solutions-essentially identifying which accidents could benefit most from digitalization efforts.

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II. Literature Review

A. Accident Definition and Data Reliability

While the definition of an accident is well-established, research increasingly focuses on uncovering causal patterns and systemic factors [8]. Nonetheless, all accidents—regardless of whether they involve physical harm or material loss—should be taken seriously. Even incidents that appear minor or cause no immediate damage may serve as warnings for more serious accidents in the future.

Many studies in the literature have highlighted concerns regarding the quality of data found in official accident reports [9, 10]. Salguero-Caparros et al. (2015) reviewed several empirical investigations into how occupational accident reports are conducted. Some classification and analysis methods for accidents lack a consistent taxonomy of contributing factors, giving analysts flexibility that can reduce the reliability and comparability of findings [11]. Hola et al. (2018) emphasized the need for a standardized approach to accident analysis to ensure consistency and allow meaningful comparisons between different studies. To address this, a methodology was proposed for categorizing the causes of occupational accidents involving construction scaffolding into three broad groups: technical, organizational, and human factors. This structured approach enables better use of database information for prioritizing and designing preventive measures [12]. Ayhan and Tokdemir (2018) reviewed literature on extracting accident-related information from databases, which are essential for identifying causes and improving safety systems. They developed a methodology for analyzing incidents, including both accidents and near-misses, based on data collected directly from construction sites [13]. While this method proved more effective than previous approaches due to its grounding in real-world data, it is also highly dependent on the analysts' expertise and can be resource-intensive in terms of time and effort. As an alternative, some researchers recommend using compensation authority databases to gather accident information and derive safety indicators [14, 15].

B. Root Causes of Construction Accidents

Understanding the causes behind construction accidents has long been a focal point of research in safety management. In a study conducted in Thailand, Pipitsupaphol and Watanabe (2000) identified several major contributors to construction accidents, highlighting the unique nature of the industry, job site conditions, unsafe equipment and methods, human behavior, and management deficiencies. They concluded that many immediate causes stem from the failure to use personal protective equipment (PPE), improper loading or placement of tools and materials, neglect in securing or warning co-workers, and incorrect use of equipment [16].

Similarly, Kartam et al. (2000), in their investigation of construction sites in Kuwait, outlined a diverse set of accident causes. These included high worker turnover, unsafe acts, poor safety performance, disorganized site conditions, inadequate maintenance of tools, supervisory errors, and the presence of unusable materials—all pointing toward systemic and behavioral shortcomings that could be prevented [17].

A more detailed classification was provided by Abdelhamid & Everett in 2000 through their study in the U.S. construction industry. They categorized causes into two broad groups: human and physical [18]. Human-related causes included actions like failing to secure or warn others, not wearing PPE, engaging in horseplay, using defective tools, and working without authority or at unsafe speeds. Physical causes, on the other hand, involved unsafe acts of others, hazardous environments, fire risks, poor housekeeping, inadequate safety guards, improper personnel assignment, and disregard for known safety procedures. Underlying all these findings is a fundamental truth: accidents don't just happen—they are caused. According to Ridley (1986), 99% of accidents arise from either unsafe acts, unsafe conditions, or both. Unsafe acts are deviations from established safety procedures that allow accidents to occur, while unsafe conditions refer to hazardous physical environments that directly lead to incidents [19]. Most construction accidents, in fact, result from a combination of these two elements. Importantly, the evolution of accident theories has shifted from merely blaming workers or defective machinery to a broader understanding of organizational and managerial responsibilities. Modern accident models aim to uncover the root causes to drive lasting improvements. Addressing surface-level issues is not enough—permanent progress in accident prevention demands tackling the root causes that lie beneath both unsafe actions and conditions.

C. Immediate Causes of Construction Accidents

Several studies have investigated the most common types of accidents occurring on construction sites. A study reported that falls (22.2%), stepping on objects (18.2%), and being struck by falling objects (17.1%) were the top three accident types identified by respondents. These incidents are often linked to inadequate fall protection, poor housekeeping, and unsafe work practices, for instance, failure to properly secure materials during lifting or transportation. These findings are consistent with recent statistics from SOCSO in Malaysia, which also highlight falls as the leading cause of construction accidents nationwide [20].

Similar patterns were observed by Pipitsupaphol and Watanabe (2000) in their analysis of construction sites in Thailand [16]. They identified the most frequent accidents as being struck by falling objects, stepping on or colliding with objects, and falls from height. In the U.S., data from International Labour Organization (2005) and studies by Huang et al. (2003) likewise confirm that falls and falling objects remain the leading causes of injuries and fatalities in the construction industry [21]. Schriver (1997) also emphasized that falls from roofs were the primary cause of fatal accidents on construction sites, attributing this to issues such as inadequate scaffolding, unprotected edges and openings, improper demolition practices, and unsafe use of ladders and hoists [22].

Being struck by falling tools, equipment, or materials is another recurring hazard in construction. These incidents often result from a lack of toe boards on scaffolding, the absence of tool belts, poor material storage, and general disorganization on site. To mitigate fall-related accidents, researchers have stressed the importance of proper scaffolding installation, ensuring structural stability, and the use of personal protective equipment (PPE) for workers at height. Comprehensive hazard identification and elimination measures are also critical in reducing such risks. In addition, exposure to electrical currents was cited by 10.8% of respondents as a significant type of accident, underscoring the need for strict electrical safety protocols [20].

D. Digitalization in Construction Safety

In many cases, traditional safety measures are insufficient to address the dynamic and diverse risks that exist on construction sites. The integration of the Internet of Things (IoT) offers a transformative approach to improving safety protocols through real-time monitoring and predictive hazard prevention. IoT refers to the interconnection of devices and sensors that collect and exchange data to enable informed decision-making and timely intervention. In the context of construction, IoT applications have demonstrated significant improvements in safety outcomes [23].

Research by Wong et al. (2020) highlights the effectiveness of an IoT-based safety model that provides real-time monitoring of personnel and environmental conditions, identifying near misses and reducing accident rates [24]. In addition, IoT technologies facilitate the integration of environmental monitoring, equipment management and predictive maintenance, which are critical to improving safety and operational efficiency on construction sites. According to research, these IoT applications contribute significantly to safer and more productive construction operations [25].

Golovina et al. (2016) present a novel approach to enhancing construction site safety through the generation of predictive heat maps aimed at identifying potential struck-by and near-miss interactions between workers-on-foot and construction equipment. Traditional safety management practices often rely on post-incident analysis, which limits proactive intervention. In contrast, this study introduces a hazard index model derived from real-time spatiotemporal data collected via GPS technologies, enabling the visualization of high-risk zones on dynamic construction sites. These heat maps allow safety managers to identify patterns of hazardous proximity and implement targeted interventions before accidents occur. The research integrates data-driven hazard analysis with Building Information Modeling (BIM) to produce actionable visualizations that reflect the real-time risk environment [26].

Yang et al. (2012) propose an integrated information management model aimed at proactively preventing struck-by-falling-object accidents on construction sites. Recognizing the significant safety risks posed by falling objects, the authors analyze historical accident data to identify common object types involved in such incidents [27]. Building upon this analysis, they developed a model that utilizes a ZigBee RFID sensor network to monitor and manage the movement of both workers and materials in real time. This system facilitates the tracking of critical objects and personnel, enabling timely interventions to prevent accidents before they occur. The proposed model represents a shift towards proactive safety measures, leveraging real-time data to enhance situational awareness and decision-making on construction sites [28].

Newaz et al. (2022) provide a comprehensive review and assessment of technologies aimed at mitigating the risk of falling from height (FFH) on construction sites. Recognizing FFH as a leading cause of injuries and fatalities in the construction industry, the authors conducted a scoping review of 86 studies published between 2010 and 2021. They identified seven key technologies contributing to FFH risk management: safety risk assessment and propagation, real-time sensing and monitoring, automated prevention through design, ontology and knowledge modeling, virtual reality for FFH training, personal fall arrest systems, and collective fall protection systems. The study further evaluated the feasibility of implementing these technologies on construction sites, considering factors such as cost, complexity, and adaptability to various project scales. The findings offer valuable insights for selecting appropriate technologies to enhance FFH safety measures in construction projects [29].

While extensive research and statistical data exist on construction safety, improving safety standards must be tailored to the specific context of each country and company. It is not effective to generalize one company's safety needs based on another's, especially when disparities in development exist. For instance, in lower-income countries, addressing basic safety requirements, such as ensuring proper use of Personal Protective Equipment (PPE), often takes priority over implementing advanced digital systems for accident prediction. In such cases, meeting fundamental safety standards should precede the adoption of smart technologies.

Moreover, evaluating a company’s safety performance requires a clear understanding of the types of accidents that occur and the technologies currently in place. This helps determine whether incidents are due to gaps in risk coverage, weak management practices, or unsafe behaviors by workers. Therefore, in the following section, we will begin by identifying the major risks outlined by the company and the technologies they have adopted. We will then classify the accidents, ranging from fatal to minor, and analyze their root causes. This will allow us to assess which incidents could have been prevented through digital solutions.

III. Analyzing Safety Challenges in Practice

This study was conducted to generate insights and recommendations specifically beneficial to our partner company. As one of the largest construction firms in Europe, this organization operates globally across sectors including buildings, infrastructure, transportation, and large-scale development projects. The company's research division is actively investing in the integration of digital technologies to enhance safety management through intelligent systems.

With a highly developed safety department, the company adheres to internationally recognized best practices. Their safety framework includes comprehensive personal protective equipment (PPE) provisions, optimized site layouts, professional training programs, and strict maintenance protocols for machinery and tools. Several years ago, the organization identified a set of high-priority risks to focus preventive efforts. These include falls from height, lifting operations, worker-equipment interaction, structural stability, and hazardous energy sources. Despite the structured approach and involvement of specialized safety professionals, incidents continue to occur. To better understand and address these gaps, accident data from 2023 and early 2024 have been collected and analyzed in this research, to uncover underlying causes and propose actionable solutions.

IV. Overview and Analysis of Recorded Accidents

A. Classification of Accidents

To streamline the analysis and highlight the most critical incidents, we began by categorizing the recorded accidents into five distinct classifications. This structured approach allowed for a clearer understanding of the severity and impact of each case type. The categories are defined as follows:

Fatal Accidents: Incidents where the worker either lost their life or suffered injuries that rendered them permanently unable to return to work.

Lost Time Accidents (LTA): Cases where the injured worker was unable to perform their duties for an extended period, typically several weeks, before resuming work.

Restricted Work Cases (RWC): Situations in which the worker could continue working but only under modified conditions or with reduced intensity for a limited time.

Medical Treatment Cases (MTC): Injuries that required professional medical attention (e.g., visiting a doctor), but the worker returned to duty immediately without long-term consequences.

First Aid Cases (FAC): Minor injuries that were treated on-site (e.g., applying a bandage or rinsing a wound), allowing the worker to resume tasks immediately without leaving the site.

The distribution of accident data collected from 2023, and part of 2024 is presented in Figure 1.

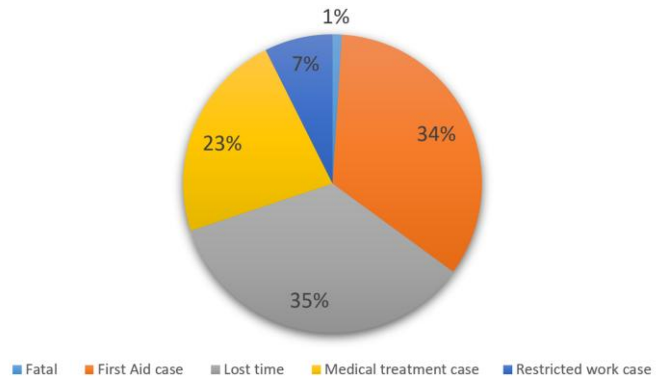

Fig. 1. Classification of Workplace Accidents and Their Distribution.

As this study focuses on addressing the most hazardous and impactful incidents, particular attention will be given to analyzing fatal accidents and lost time accidents. Although fatal accidents represent only 1% of the total, their severity makes them a critical area of concern. However, due to their relatively low occurrence, relying solely on this category would limit the scope of the analysis. Therefore, lost time accidents, which account for 35% of the total cases, will also be included. By combining these two categories, the analysis will cover 36% of all reported accidents, enabling a more comprehensive understanding of the most serious safety issues and supporting more effective risk mitigation strategies.

B. Causes of Fatal and Lost Time Accidents

Following a preliminary analysis of the collected data, the root causes of both fatal and lost time accidents were identified and are presented in Table 1. The results show that working at height was the leading cause, accounting for 23.7% of the cases, followed by being struck by an object at 19%, vehicle-related incidents at 16.5%, and machine handling and lifting operations at 10.9%. The remaining 29.9% were categorized under other causes, which include a variety of less frequent but still significant incidents.

These findings are consistent with trends highlighted in the literature, reinforcing the fact that certain risks remain persistent and critical in construction environments. Given their prevalence and severity, this study will place a particular emphasis on the top two causes—working at height and being struck by an object. To gain deeper insights, we will conduct a case-by-case analysis of these accidents to determine their specific root causes. Additionally, we will examine the body parts most frequently injured in these incidents to explore whether this information can contribute to improved prevention strategies or targeted protective measures.

C. Injury Patterns in Major Accidents

An analysis of injury data from fatal and lost-time accidents shows that the skull (9.02%), ankle (8.51%), back (6.96%), arm (6.70%), and shoulder (6.44%) are among the most affected body parts. Other areas, such as the wrist, hand, eyes, and fingers, each account for around 5–6%, while feet have a slightly lower rate at 4.38%, as shown in Figure 2. However, upon reviewing the incident reports, it becomes clear that workers were wearing the appropriate personal protective equipment (PPE) at the time of the accidents. This leads to an important conclusion: in most cases, especially falling from height, injuries are not necessarily linked to the absence of PPE or to a specific body part. The relatively close percentages across various body parts suggest that when a worker falls, any part of the body may be impacted, reinforcing the need for comprehensive fall prevention measures rather than reliance solely on protective gear.

TABLE I: CAUSES OF FATAL AND LOST TIME ACCIDENTS

Causes	Percentage
Falling from Height	23.7%
Being Struck by an Object	19%
Vehicle-Related Incidents	16.5%
Machine Handling and Lifting Operations	10.9%
Others	29.9%

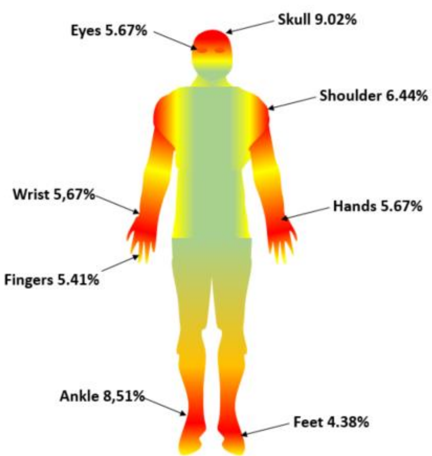

Fig. 2. Heatmap of Injury Distribution Across the Human Body

D. *Accident Circumstances in Practice*

After analyzing the accident records within the company and identifying the most affected body parts, we now focus on the specific scenarios behind falls from height and incidents of being struck by objects (see Table 2).

Although these accidents may share the same immediate causes, the circumstances, locations, and sequences leading to them vary significantly. Our review of the reports revealed that 20% of fall-related accidents occurred from ladders or scaffolding, while 17% involved falls through openings. Notably, 8% of those affected were not wearing PPE, as the incidents happened during breaks or while exiting the site, rather than during active work. Additionally, 9% of falls resulted from the collapse of temporary structures, including scaffoldings and formworks.

As for accidents involving workers being struck by objects, the data shows that 36% were caused by falling materials or tools during work operations. Another 20% were due to detached parts of frameworks or scaffolding, while 6% were linked to strong winds dislodging structural elements. Finally, 6% of incidents occurred when components fell from trucks (camions) during loading or unloading. These findings highlight the diversity of hazardous scenarios even within a single cause category, underscoring the importance of context-specific safety measures.

TABLE II: SCENARIOS LEADING TO SEVERE ACCIDENTS

Type of accident	Scenario	Percentage
Falling from Height	From ladders or scaffolding	20%
	From openings	17%
	No PPE (during breaks or leaving site)	8%
	Collapse of temporary structures	9%
Struck by Object	Falling materials or tools during work	36%
	Falling parts of framework or scaffolding	20%
	Wind-induced fall of frameworks	6%
	Falling elements from trucks (camions)	6%

E. *Prioritizing Digital Solutions for Accident Scenarios*

While analyzing the most frequent accident scenarios, it's clear that not all of them warrant the use of complex digital systems. A selective, pragmatic approach is necessary — one that leverages digitalization where it brings real added value, and relies on simpler, cost-effective solutions where appropriate.

For falls from height, scenarios like falling from openings or the collapse of temporary structures present a strong case for digital intervention. These events often occur without warning and can be addressed through digital twins, structural health monitoring, or real-time worker location tracking. By identifying structural weaknesses or alerting workers in dangerous areas, these tools can prevent severe accidents and reduce response times.

However, incidents like falling from ladders often have more straightforward solutions. For example, using a safety belt or harness attached to the worker is not only more affordable but also highly effective. In such cases, adding a digital twin system would be unnecessarily complex and financially inefficient.

Similarly, in the case of being struck by objects, falling tools or materials during work often result from carelessness or poor handling — issues that occur even in domestic settings. These scenarios are best addressed through proper training, tool securing practices, and safety culture reinforcement rather than digital monitoring. A digital system won't prevent a hammer from slipping out of a worker's hand — but a simple tether might.

That said, some object-related incidents do benefit from digital solutions. For instance, falling parts of frameworks or wind-induced collapses of structures can be predicted or monitored through sensors and alert systems. Likewise, material falling from trucks can be reduced through automated loading checks or video analytics that ensure proper securing.

In conclusion, the goal isn't to digitize everything, but to digitize smartly — using technology where it adds safety and efficiency and relying on common-sense measures where they are more appropriate.

V. Enhancing Scaffolding Safety through Dynamic Digital Twin Integration

So far, we have examined various types of accidents that occur in the construction industry, supported by relevant statistics and an analysis of their root causes. We then explored strategies for accident prevention, particularly through the use of digital tools.

As an example of a digital solution for accident prevention, our laboratory developed a digital twin (DT) framework aimed at improving scaffolding safety. This framework enables real-time monitoring of key parameters such as wind loads, worker loads, structural load distribution, and overall scaffolding stability, with a strong emphasis on structural analysis and safety enhancement.

The development of a Digital Twin (DT) for scaffolding safety involves the creation of a comprehensive and dynamic virtual representation of the physical scaffolding system. The process starts with modelling the scaffold structure using Autodesk Robot Structural Analysis, which allows accurate simulation of structural behaviour under different loading and environmental conditions. Key parameters such as load distribution, joint stiffness, wind effects and worker activity levels are identified and incorporated into the model. Multiple scenarios are simulated, including both standard operations and potential hazard situations, to assess structural performance and safety margins. This allows adverse cases, such as overload, instability or structural deformation, to be identified in advance. Real-time data from embedded sensors (e.g. strain gauges, accelerometers, inclinometers, etc.) is continuously fed into the DT system to monitor deviations from safe conditions. When an anomaly or threshold violation is detected, an automated alarm system is triggered to alert workers and site managers, enabling immediate preventive action. This DT framework supports predictive safety planning, real-time monitoring and proactive risk mitigation on scaffolding structures.

VI. Conclusion and Future Direction

This study has explored the primary accident types occurring on construction sites—particularly falls from height and incidents of being struck by objects—through a detailed analysis of internal accident reports. The findings revealed that even with proper use of personal protective equipment (PPE), injuries still occur across various body parts, with no single area significantly more affected than others. This suggests that in many cases, the severity of these accidents goes beyond what PPE alone can prevent.

By examining the specific scenarios behind these incidents—such as falls from scaffolding, unprotected openings, or collapsing temporary structures, as well as falling tools or materials—it became evident that each requires a different mitigation approach. Some of these, like structural collapses or wind-induced hazards, may benefit from digitalization techniques, such as real-time monitoring through digital twins. These tools can help predict and prevent failures, enhancing overall site safety.

However, not all accident scenarios justify high-tech interventions. Issues like falls from ladders or tools slipping during manual work can often be addressed more effectively with simple and affordable safety measures, such as better training or tethering systems. These types of incidents are common even in non-construction settings, underscoring the importance of integrating basic human-centered safety practices alongside advanced technologies.

Importantly, this study can serve as a foundation for future research and a reference point for companies with similar operational standards that are considering digitalizing their safety systems. By identifying which accident scenarios can truly benefit from digital solutions, this work helps pave the way for targeted, efficient, and cost-effective digital transformation in construction site safety management.

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