OCCUPATIONAL HAZARDS AND SAFETY MEASURES IN LARGE-SCALE CONSTRUCTION PROJECTS

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ABSTRACT

Large-scale construction projects play a pivotal role in global economic growth, yet they expose workers to significant occupational hazards due to complex operations, heavy machinery, and evolving site conditions. This study examines the main dangers that together cause the bulk of industry fatalities: electrocution, falls from heights, struck-by and caught-in-between events, and ergonomic and chemical hazards. Drawing on global statistics, empirical studies, and case analyses, the paper evaluates the effectiveness of safety interventions, including regulatory frameworks, technological solutions (BIM, wearable sensors, drones, AI-based monitoring), and behavioral measures (training and integrated safety management systems). Findings reveal that while regulations reduce incident rates by 20–30% and technologies enhance hazard detection by up to 50%, inconsistent enforcement, high costs, and resource limitations remain barriers, particularly in developing countries. The study concludes that integrated, adaptive safety ecosystems are essential for reducing risks, protecting workers, and enhancing efficiency in large-scale construction projects.

Keywords: Occupational hazards, safety measures, construction projects, risk management, worker safety.

INTRODUCTION

Large-scale construction endeavors, encompassing tall edifices, bridges, and infrastructural advancements, are crucial to the advancement of the global economy, making substantial contributions to Gross Domestic Product and urban growth (Veres et al., 2024). Nevertheless, these undertakings subject laborers to considerable occupational hazards owing to their intricate operational frameworks, which entail the utilization of heavy machinery, coordination among multiple contractors, and ever-evolving work environments. Occupational hazards refer to the risks and dangers that individuals encounter in their workplaces, while occupational diseases arise from these exposures (Awodele et al., 2014; Packard, 1989). Although such diseases may be less prevalent than other significant health issues, they still impact a substantial number of individuals, especially in rapidly industrializing nations like Nigeria, thereby exerting an indirect influence on the economy (Awodele et al., 2014; Toscano & Jack, 1996). Workers are exposed to a wide array of hazards during their employment, which can include chemical substances, biological agents, physical factors, and poor ergonomic conditions. These various hazards can lead to a range of health problems (Aliyu & Shehu, 2007; Awodele et al., 2014). The construction sector, constituting 7% of global employment, is accountable for over 30% of occupational fatalities, with extensive projects exacerbating risks due to their magnitude and logistical complexities (ILO, 2022). Significant hazards encompass falls from elevated heights, which account for nearly 40% of fatalities in the U.S. construction industry, incidents involving being struck by objects and caught in/between circumstances (25% of injuries), electrocution, and ergonomic-related injuries (BLS, 2024a; OSHA, 2025). In industrializing countries, insufficient safety regulations and inadequate training amplify these risks, resulting in elevated rates of injury and economic detriment (Moyce & Schenker, 2018). For instance, Nigeria's construction industry grapples with challenges stemming from limited enforcement mechanisms and resource limitations, thereby increasing the susceptibility of workers. To mitigate these hazards, it is imperative to implement comprehensive safety protocols, which encompass regulatory frameworks, technological advancements, and educational programs. Regulatory standards provide essential guidelines for hazard mitigation, while technological innovations, including Building Information Modeling (BIM), wearable sensors, and artificial intelligence-based monitoring systems, significantly enhance safety outcomes (Pereira et al., 2025; Usama et al., 2024; Wong & Lee, 2022). Nevertheless, global disparities in the adoption of these measures, particularly within developing regions, underscore the necessity for adaptive strategies (Adetomi Adewnmi et al., 2023; Rustamova et al., 2025). This research endeavor seeks to examine the predominant occupational hazards present in large-scale construction projects and assess the efficacy of safety interventions aimed at their mitigation. By integrating global data, case studies, and contemporary literature, this paper contributes to the field of occupational health and safety (OHS) research and offers actionable recommendations for various stakeholders, including project managers, policymakers, and safety professionals. The following sections will examine key occupational hazards in large-scale construction, including falls, struck-by and caught-in/between incidents, electrocution, and ergonomic risks, while assessing effective interventions (Almaskati et al., 2024). These sections will highlight the essential role of integrated safety management systems in tackling the complex challenges present in diverse global construction environments.

1. Occupational Hazards in Large-Scale Construction

The interpretation of the term "hazard" can often present challenges (Lama et al., 2019). Frequently, precise definitions are either absent in lexicons or are conflated with the term "risk" (Lama et al., 2019). For instance, one dictionary characterizes a hazard as "a danger or risk," thereby elucidating the rationale behind the interchangeable usage of these terms by numerous individuals (Lama et al., 2019). Fundamentally, a hazard denotes the capacity to inflict harm or engender an adverse impact (for instance, on individuals in terms of health repercussions, on organizations concerning property or equipment damages, or on the environment) (Brauer, 2022; Lama et al., 2019). Occasionally, the resultant harm is erroneously designated as the hazard rather than the actual origin of the hazard (Lama et al., 2019). For example, the ailment tuberculosis (TB) may be termed a "hazard" by some; however, more generally, the bacteria that induce TB (Mycobacterium tuberculosis) would be classified as the "hazard" or "hazardous biological agent" (Lama et al., 2019; Matuka & Singh, 2017). Large-scale construction projects pose particular risks because of their size, duration, and operational complexity. This section classifies important dangers according to global occurrence data and industry reports.

2.1 Falls from Height

Falls constitute the predominant cause of severe injuries (48%) and fatalities (30%) within the realm of construction accidents (Hu et al., 2011; Nadhim et al., 2016). Specifically, falls from heights (FFH) account for over one-third of construction-related injuries and rank among the principal causes of both serious injuries and fatalities (Nadhim et al., 2016; M. Zhang & Fang, 2013). In the year 2013, FFH represented 36.9% of occupational fatalities in the United States (BLS, 2024b), 31% in the United Kingdom (Nadhim et al., 2016), and 12% in Australia. A multitude of studies have employed diverse methodologies, including survey questionnaires, interviews, case studies, forensic data, morbidity records, and empirical/experimental laboratories, to elucidate the factors contributing to falls (Nadhim et al., 2016). Nonetheless, the intricate and multidimensional relationships among these factors have not been comprehensively examined (Nadhim et al., 2016). Prior review articles have predominantly focused on a narrow range of interventions, such as influences on activities, scaffolding/platform issues, or fall prevention measures, alongside field research pertaining to workers' behavior (Hu et al., 2011; Nadhim et al., 2016). The fatalities and serious injuries associated with falls in construction have garnered significant scholarly interest (Nadhim et al., 2016). For example, Hu et al. (2011) provided a comprehensive overview of the factors that influence fall risks in a general context. While such an overarching perspective on factors is beneficial, it is noteworthy that the majority of the reviewed literature was published before 2009, and several studies did not primarily concentrate on fall incidents (Nadhim et al., 2016). More recently, Jebelli et al. (2014) have undertaken a study aimed at validating the efficacy of postural stability metrics. However, it is imperative to first address the critical factors associated with FFH and subsequently devise or develop targeted solutions to diminish or mitigate the occurrence of fall incidents (Nadhim et al., 2016). Table 1 provides a foundation for comprehending and reducing this common hazard by summarising seven important studies that address the crucial problem of falls from height in large-scale construction. These studies include risk factors, empirical data, and prevention strategies (Halabi et al., 2022; Abdul Halim et al., 2022).

Table 1: Summary of Literature on Falls from Height in Construction: Key Findings and Relevance to Large-Scale Projects

Title	Key Findings	Relevance to Topic	Citations
Falls from Height in the Construction Industry: A Critical Review of the Scientific Literature	Identifies key FFH factors: risky activities, individual characteristics, site conditions, and scaffolds/ladders. FFH accounts for 36.9% of U.S. construction fatalities in 2013.	It provides a foundational review of FFH causes, critical for understanding hazards in large-scale projects.	(Nadhim et al., 2016)
Risk Factors and Emerging Technologies for Preventing Falls from Heights at Construction Sites	Analyzes 94 articles (2002–2022), identifying missing guardrails, lack of PPE, and poor training as top FFH hazards. Recommends integrated tech systems (e.g., BIM, drones).	Highlights technological interventions for FFH prevention, relevant for safety measures in large projects.	(M. Khan et al., 2023)
A Review and Assessment of Technologies for Addressing the Risk of Falling from Height on Construction Sites	Reviews 94 articles, noting that traditional methods (e.g., harnesses) are insufficient. Proposes seven tech solutions, including real-time monitoring and VR training.	Emphasizes advanced tech for FFH prevention, directly applicable to modern large-scale construction safety.	(Tanvi Newaz et al., 2022)
Causal Factors and Risk Assessment of Fall Accidents in the U.S. Construction Industry: A Comprehensive Data Analysis (2000–2020)	Analyzes 23,057 OSHA-reported fall accidents, showing FFH as 50% of U.S. construction accidents. Notes: limited improvement in fall protection use.	Offers empirical data on FFH prevalence, crucial for hazard analysis in large projects.	(Halabi et al., 2022)
Preventing Fall-from-Height Injuries in Construction: Effectiveness of a Regulatory Training Standard	Evaluates Ontario's 2015 WAH training, showing a 19.6% reduction in targeted fall injuries. Suggests training alone is insufficient without higher-tier controls.	Demonstrates the training's role in FFH prevention, relevant for workforce safety measures.	(Robson et al., 2020)
An Evaluation of the Technologies Used for the Real-Time Monitoring of the Risk of Falling from Height in Construction	Reviews 40 articles on real-time monitoring tech (e.g., AI, sensors). Finds they enhance hazard detection but don't replace primary prevention.	Focuses on real-time tech solutions, key to dynamic safety management in large projects.	(Pereira et al., 2024)
Risk Assessment of Falling from Height in the Construction Industry in the Northern Region of Peninsular Malaysia	Uses SEM to identify worksite conditions and resource management as key FFH risk factors. Notes: PPE misuse is a major issue.	Provides regional insights into FFH risks, applicable to site-specific safety plans.	(Abdul Halim et al., 2022)

According to Nadhim et al. (2016), falls from heights accounted for 36.9% of construction-related deaths in the United States in 2013, and by 2020, that number will rise to 50% of accidents (Halabi et al., 2022). Falls from heights continue to be the major cause of construction fatalities. This increase highlights ongoing difficulties in large-scale projects, where dangers are increased by elevated labour, scaffolding, and complicated site conditions. The table identifies key risk factors that correspond with the dynamic and multi-contractor contexts of large-scale construction, such as inadequate personal protective equipment (PPE), poor training, and missing guardrails (Khan et al., 2023; Abdul Halim et al., 2022). These findings highlight the importance of site-specific safety measures, particularly in areas like Malaysia, where resource restrictions increase PPE misuse (Abdul Halim et al., 2022). Khan et al. (2023) and Tanvi Newaz et al. (2022) advocate for Building Information Modelling (BIM), drones, and real-time monitoring systems such as AI and sensors to improve hazard detection but not replace primary prevention (Pereira et al., 2024). However, Robson et al. (2020) warn that training alone, such as Ontario's 2015 Working at Heights program, results in just a 19.6% reduction in injuries without higher-tier controls. This shows that large-scale projects necessitate integrated safety systems that combine engineering controls (for example, guardrails) with administrative safeguards.

2.2 Struck-by and Caught-in/Between Incidents

A caught-in/between accident, commonly designated as a caught-in or caught-between incident, constitutes a workplace occurrence wherein an individual becomes ensnared, immobilized, or compressed between two or more entities (C.-F. Chi & Lin, 2018; Darda'u Rafindadi et al., 2025). Such incidents predominantly transpire within industrial environments, encompassing construction sites, manufacturing establishments, agricultural enterprises, and storage facilities (Darda'u Rafindadi et al., 2025). Employees may find themselves ensnared between the moving components of machinery, including gears, rollers, belts, or hydraulic mechanisms (C.-F. Chi & Lin, 2018; Darda'u Rafindadi et al., 2025). For example, an individual's attire or body part may become engaged in a conveyor system or may become entrapped between gears during their operational cycle (Darda'u Rafindadi et al., 2025). Additionally, accidents may arise when individuals are wedged between substantial objects, such as construction materials (e.g., concrete slabs, steel beams), collapsed edifices, or vehicles (e.g., forklifts, trucks) (Bhole, 2016; Darda'u Rafindadi et al., 2025). Moreover, employees may become ensnared within trenches or excavations due to cave-ins, soil collapses, or descending debris (Darda'u Rafindadi et al., 2025; Hayslip, 2013). Objects descending from elevated positions or inadequately stored materials can similarly ensnare or impact workers situated below, thereby resulting in caught-in/between injuries (C.-F. Chi & Lin, 2018; Darda'u Rafindadi et al., 2025). Furthermore, individuals can be caught amid collapsing walls, roofs, or scaffolding frameworks (Darda'u Rafindadi et al., 2025; Veasey et al., 2005). Operating within confined spaces that possess limited avenues for egress may result in employees becoming trapped or caught should an incident transpire (Darda'u Rafindadi et al., 2025; Veasey et al., 2005).
Caught-in/between accidents frequently culminate in grave injuries, including fractures, amputations, crush injuries, and, in extreme circumstances, fatalities (Darda'u Rafindadi et al., 2025). Preventative strategies generally concentrate on engineering controls (e.g., machine safeguarding, safety barriers), administrative measures (e.g., training, safe operational procedures), and personal protective equipment (PPE) to mitigate the likelihood of such accidents (Darda'u Rafindadi et al., 2025). Systematic inspections, hazard evaluations, and compliance with safety protocols are paramount in lessening the incidence of caught-in/between accidents in occupational settings (Darda'u Rafindadi et al., 2025).

2.2.1 Number of Cases Analyzed

Research examining caught-in/between accidents across multiple nations and timeframes demonstrates a variety of methodological approaches alongside a broad spectrum of cases analyzed, encompassing both fatal and non-fatal incidents.
Numerous investigations have underscored the substantial incidence of occupational fatalities within the construction industry (Darda'u Rafindadi et al., 2025). An examination of 1230 occupational fatality reports from the years 1989, 1990, and 1992 indicated that 53.82% of these fatalities transpired within the construction sector, with caught-in/between and clamped accidents representing 7.9% of fatal occurrences (Darda'u Rafindadi et al., 2025). Similarly, from 1997 to 2004, 4333 out of 10,276 occupational fatalities were recorded in the construction industry (Darda'u Rafindadi et al., 2025). Among these, 122 deaths (2.8%) were attributed to machinery-related caught-in accidents, while 417 deaths (9.6%) resulted from structural collapses (Chinniah, 2015;

Çoktu et al., 2024; Darda'u Rafindadi et al., 2025). Investigations concentrating on heavy machinery and equipment further illuminate their role in construction-related fatalities (Almaskati et al., 2024; Darda'u Rafindadi et al., 2025; Hinze & Teizer, 2011). Between 1992 and 2002, an analysis of 253 heavy equipment-associated deaths within the excavation sector revealed that 12% were attributable to caught-in/between accidents involving vehicles (Darda'u Rafindadi et al., 2025). Another inquiry into dump truck-related incidents from 1992 to 2007 documented 829 fatalities among construction workers, with 56 deaths specifically linked to caught-in/between accidents (Darda'u Rafindadi et al., 2025). In the United States, a study analyzing 9358 construction industry accidents from 2002 to 2011 found that 10% (934 accidents) were categorized as caught-in/between incidents (S. Chi et al., 2012; S. Chi & Han, 2013; Darda'u Rafindadi et al., 2025). Similarly, data from Malaysia between 2005 and 2009 indicated that 1855 out of 19,195 occupational accidents occurred within the construction sector, with caught-in/between accidents reported at an average annual rate of 371 cases (Darda'u Rafindadi et al., 2025). In Spain, a review of 1,630,452 construction accidents from 1990 to 2000 revealed that 98% were classified as minor, while serious accidents and fatalities constituted 1.8% (28,658 cases) and 0.2% (3029 cases), respectively (Darda'u Rafindadi et al., 2025). Investigations of specific projects further highlight the hazards associated with construction activities. An analysis of 378 accidents from the Hong Kong–Zhuhai–Macao Bridge project (2012–2017) determined that falls from heights represented the most prevalent fatal accident, followed by caught-in/between incidents, which accounted for one in nine fatal accidents (Darda'u Rafindadi et al., 2025). In Qatar, an examination of 84 non-fatal occupational accidents within a ready-mixed concrete enterprise indicated that 71% were attributed to unsafe behaviors, such as improper utilization of personal protective equipment (PPE) (Darda'u Rafindadi et al., 2025; Prasetyo et al., 2022). Larger datasets yield a more comprehensive understanding of patterns associated with construction-related accidents. The Occupational Safety and Health Administration's (OSHA) fatality database pertaining to truss work, covering the years 1990 to 2009, recorded a total of 214 fatalities attributable to catastrophic events, thereby underscoring the hazards associated with bracing methodologies and material hoisting operations (Craighead, 2009; Darda'u Rafindadi et al., 2025). Furthermore, an examination of 763 incidents documented in the Construction Safety Management Integrated Information (CSI) system in South Korea uncovered 203 instances of significant risk, predominantly stemming from vehicle-utilized construction apparatus and malfunctioning protective equipment (Darda'u Rafindadi et al., 2025). Investigations into the causation of accidents offer essential perspectives regarding fatalities. A meticulous analysis of 100 case files employing social network analysis (SNA) as a methodological framework revealed that numerous caught-in/between hazards were linked to human errors, such as inadequate equipment handling, insufficient competency, and disregard for personal protective equipment (PPE) usage (Darda'u Rafindadi et al., 2025). In a similar vein, a comprehensive review of 4899 autopsy reports in Japan unveiled 136 deaths resulting from occupational accidental injuries (OAIDs), with 53 of these fatalities occurring within the construction sector, primarily due to transportation machinery, including cranes and conveyor belts (Darda'u Rafindadi et al., 2025).
Smaller enterprises and specific occupational roles exhibit unique patterns concerning construction-related accidents (Darda'u Rafindadi et al., 2025). A scholarly investigation of 784 single-fatality incidents occurring between 1999 and 2000 indicated that firms employing fewer than 30 individuals were less susceptible to caught-in/between accidents (Darda'u Rafindadi et al., 2025). Concurrently, workers in the concreting sector encountered heightened risks during operations such as structural failures and earthmoving activities, as evidenced by a thorough analysis of 34 fatal incidents within the U.S. concrete industry between the years 2018 and 2019(Darda'u Rafindadi et al., 2025).

2.3 Electrocution

Electrocution constitutes a significant occupational peril within extensive construction endeavors, wherein elaborate electrical systems, provisional installations, and substantial machinery exacerbate associated risks (Rao et al., 2021; D. Zhao, 2014). Large-scale undertakings, such as the construction of skyscrapers and major infrastructure projects, encompass intricate electrical frameworks, including overhead power lines, portable tools, and temporary wiring, which significantly increase the likelihood of exposure to live circuits and incidents of arc flash (Zhao et al., 2014). Engagement with energized equipment or power lines, frequently resulting from insufficient grounding, substandard work practices, or inadequate personal protective equipment (PPE), emerges as a predominant factor contributing to these occurrences (Akintoye et al., 2025; K. A. Khan, 2014). The repercussions encompass fatalities, severe thermal injuries, amputations, and delays in project timelines, thereby highlighting the imperative for comprehensive safety protocols. In industrializing regions such as Nigeria, a deficiency in training and resources exacerbates these risks, thereby necessitating customized interventions (Gressgård, 2014). In order to ensure safety in large-scale construction environments, this section critically assesses the causes, prevalence, and effects of electrocution. It does this by drawing on recent research to inform effective preventive measures, such as insulation, grounding, and enhanced training. To delineate the scope and mitigation of electrocution hazards within the construction sector, Table 2.3 encapsulates essential findings from seven authoritative investigations, outlining risk determinants, incident trends, and safety recommendations pertinent to extensive projects (Janicak, 2008).

Table 2.3: Literature Review on Electrocution Hazards in Construction: Key Findings and Safety Implications

Title	Key Findings	Citations
Occupational fatalities due to electrocutions in the construction industry	In the United States, 997 occupational fatalities involving victims 16 years of age and older occurred between 2003 and 2006 as a result of interaction with electric current. 492 of these deaths (or around 49%) happened in the construction sector. These incidents involved, among other things, coming into contact with electric wiring, overhead power lines, or the electric current of a machine, equipment, or appliance.	(Janicak, 2008)
Electrical deaths in the US construction: an analysis of fatality investigations	An analysis of all electrical fatality investigations reveals 132 electrical safety failures. The findings highlight the most prevalent electrical safety issues on construction sites as well as the characteristics of electrical fatalities in the industry. According to this research, worker dangerous behaviours and electrical fatalities may be greatly influenced by sociotechnical system failures and the inadequacy of present safety training programs.	(D. Zhao et al., 2014)
Fatal occupational electrocutions in the United States	The Bureau of Labour Statistics Census of Fatal Occupational Injuries provided the data from 1992 to 1999. Males made up nearly all of the occupational electrocution deaths, with whites and American Indians, as well as those aged 20 to 34, having the highest rates. They were highest in firms with 10 or fewer employees, in the South, and during the summer.	(Taylor et al., 2002)
In-depth accident analysis of electrical fatalities in the construction industry	In this study, 255 electrical fatalities in the construction sector were examined. Accident causes (not de-energising electrical systems, not keeping safe distances, not using personal protective equipment (PPE), poor work practices, unintentional contact with exposed electrical parts, defective tools and equipment, lack of effective safety devices, or unsafe environment) and prevention measures (safe work practices, insulation, guarding, grounding, and electrical protective devices) were developed for each accident pattern based on the common scenarios that were identified.	(C.-F. Chi et al., 2009)
Epidemiology of electrocution fatalities	According to an analysis of farming-related dangers, electrocutions were responsible for roughly 7% of all fatalities associated with agricultural activities. The specific risks associated with these electrocutions include overhead powerlines, buried electrical cables, and internal wiring in agricultural structures. According to this study, contact with high-voltage powerlines was the cause of 61% of the 944 work-related electrocutions that occurred between 1984 and 1986. According to NIOSH, between 1980 and 1989, contact between energised, overhead powerlines and cranes or other boom vehicles resulted in an average of 15 electrocutions annually.	(Casini & Kisner, 2002)
Electrical injury in construction workers:	105 patients (52%) of the 202 patients in this study were construction workers, while the remaining 97 patients (48%) made up the remaining group. The	(Salehi et al., 2014)

A special focus on injury with electrical power	mean age, gender, and average burn size of the two groups differed significantly. Contact with overhead high-voltage power lines during work is the most frequent cause of electrical injuries among construction workers. This kind of electrical harm is linked to increased use of flaps, fasciotomies, and limb amputations.	
Causes of electrical deaths and injuries among construction workers	Electrical worker fatalities and injuries were primarily caused by contact with "live" electrical wiring, equipment, and light fixtures, with contact with overhead power lines coming in second. The leading cause of fatality among non-electrical workers was contact with overhead power wires. Additional causes included coming into contact with portable lights, power tools, machinery, and energised metal objects. Among construction workers, arc flash or blast was responsible for 31% of electrical injuries but fewer than 2% of electrical fatalities.	(McCann et al., 2003)

The incidence of fatalities due to electrocution in the construction sector exhibited a decline during the economic recession, followed by a subsequent increase, thereby reflecting the broader trend of fatal accidents within this industry (Figure 1) (Wang et al., 2017). In the year 2015, there were recorded 82 fatalities due to electrocution among construction personnel, representing a 17% increase from the 70 fatalities documented in 2011; however, this figure is less than the 26% rise in overall construction-related fatalities during the same timeframe (Wang et al., 2017). On average, from the years 2003 to 2015, approximately 9% of all construction fatalities were attributed to electrocution (Wang et al., 2017). Throughout this interval, the frequency of electrocution incidents diminished by 39%, in contrast to the 16% reduction observed in total construction fatalities, thereby continuing a protracted downward trajectory in electrocution incidents (Dong et al. 2010; Wang et al. 2015; Wang et al., 2017) and implying that interventions targeting electrocution in construction are relatively efficacious (Wang et al., 2017).

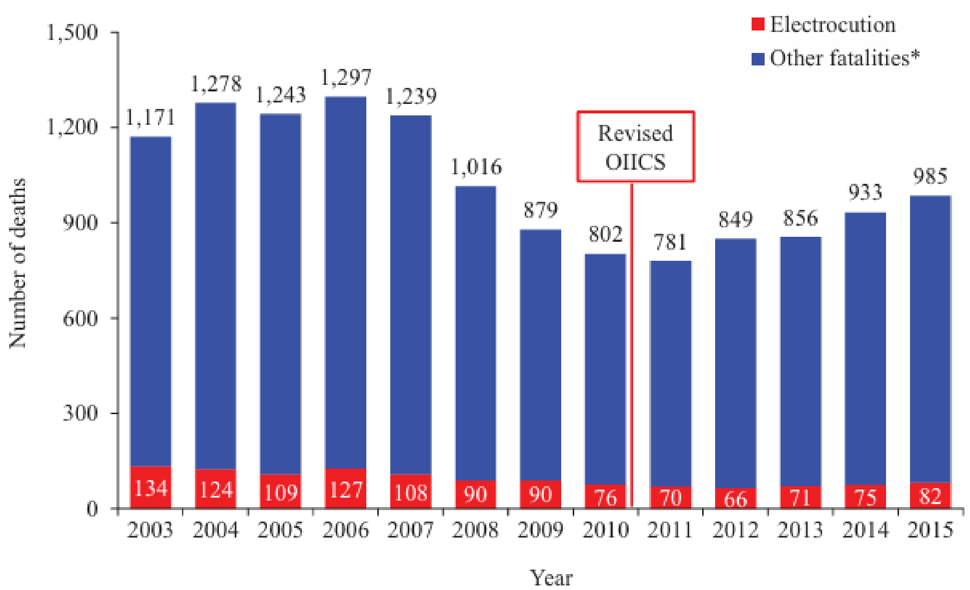

Figure 1. Number of fatalities in construction, electrocution, and other fatalities, 2003-2015 (Wang et al., 2017)

The incidence of electrocution-related fatalities within the construction sector has experienced a decline commensurate with the overall reduction in total fatalities. In the year 2015, the statistic recorded was 0.8 electrocution fatalities per 100,000 full-time equivalent workers (FTEs), representing a substantial 40% reduction from the rate of 1.3 per 100,000 FTEs observed in 2003 (Figure 2) (Wang et al., 2017). Nevertheless, the rate exhibited an increase of approximately 9% from the year 2014 to 2015 (Wang et al., 2017).

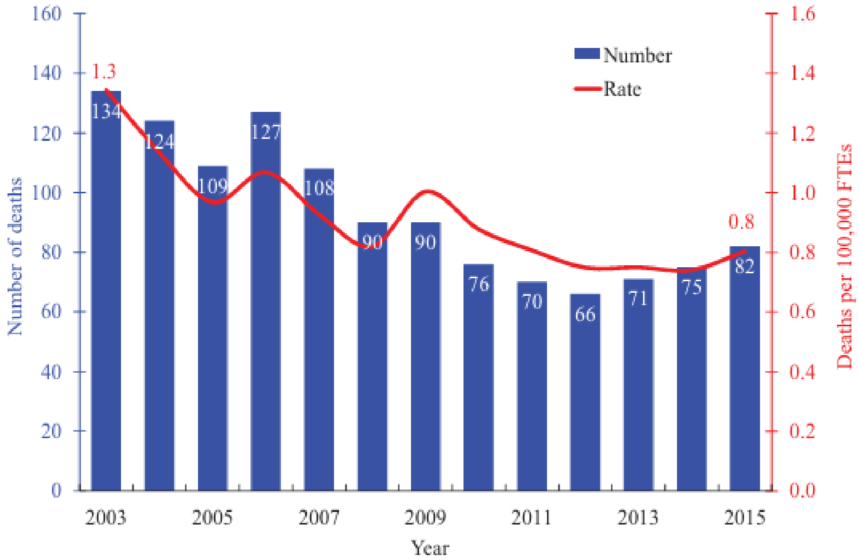

Figure 2. Number and rate of electrocutions in construction, 2003-2015 (Wang et al., 2017)

2.4 Ergonomic and Chemical Hazards

With the continuous development of the chemical industry, the production scale of chemical companies has gradually increased, resulting in frequent explosion accidents in chemical plants, causing heavy casualties and serious property losses, as well as great environmental pollution (Lu et al., 2020; L. Zhao et al., 2018). According to the accident data of the State Administration of Work Safety, from 2006 to 2015, there were 125 safety accidents in chemical companies in China, resulting in 542 deaths (Lu et al., 2020). Among them, 57 explosion accidents, accounting for 45.60% of the total number of accidents, caused a total of 301 deaths, accounting for 55.53% of the total number of deaths (Lu et al., 2020; Yanchang et al., 2017). In recent years, there have also been many serious chemical plant explosion accidents (CPEAs). Two typical examples are listed as follows: On 21 March 2019, an explosion occurred at Tianjiayi Chemical Plant in Xiangshui County, Yancheng City, Jiangsu Province, resulting in 78 deaths and direct property losses of RMB 1.986 billion (Lu et al., 2020; N. Zhang et al., 2019). On 28 February 2012, Hebei Keeper Chemical Industries Co., Ltd., located in Zhao County, Shijiazhuang, Hebei, exploded. The accident caused a total of 25 deaths and 46 injuries, with a direct property loss of RMB 44.59 million (Jiang & Han, 2018; Lu et al., 2020). Because chemical plants produce and store many kinds of flammable, explosive, and toxic materials, once the explosion occurs, its destructive power is difficult to estimate, and can even lead to secondary derivative disasters (Du et al., 2020; Lu et al., 2020). Therefore, in order to prevent and effectively mitigate the risk of accidents and analyze the causes, the development and consequences of the accidents are very important (Lu et al., 2020).

The prevailing methodologies for analyzing Chemical Process-Related Accidents (CPEAs) predominantly emerge from two analytical frameworks: statistical examination and causation modeling (Lu et al., 2020). The statistical examination encapsulates the determinants of accidents by categorizing them into cause, type, time, and geographic region, drawing upon data derived from accident cases (Lu et al., 2020). Li et al. executed a statistical examination focusing on the temporal occurrence, spatial location, physical characteristics, categories of hazardous chemicals, stages of occurrence, and causative factors of accidents, ultimately determining that explosion incidents within the production phase constituted the majority of recorded cases (Jstongdetrade, 2024; Lu et al., 2020). Causation models for accidents elucidate the underlying mechanisms of accidents and offer a theoretical structure for risk analysis and preventative measures associated with accidents (Gui et al., 2018). Early models of accident causation primarily engage with the analysis of accidents through the lens of human-centric factors (Fu et al., 2020; Lu et al., 2020), incorporating constructs such as accident-prone tendency (APT), accident liability (AL), Surry's model, Hale's accident model, and Lawrence's accident model, among others. These models predominantly emphasize the examination of accidents with a singular factor type (Lu et al., 2020). To facilitate a holistic analysis of CPEAs and delve into the more profound causative elements of accidents, scholars have integrated several more broadly utilized models into the analysis of CPEAs, including the 24 Model, the Human Factors Analysis and Classification System (HFACS), and Fault Tree Analysis (FTA) (Lu et al., 2020). Wang et al. employed the 24 Model to investigate a representative hazardous chemical accident in China, analyzing the causative factors from both individual and organizational perspectives (Lu et al., 2020; J. Wang et al., 2020). Utilizing a dataset of 102 accident cases, Wang et al. examined the primary manifestations of unsafe behavior, preconditions for unsafe conduct, inadequate supervision, and organizational influences in chemical accidents, subsequently enhancing the HFACS model to ensure its applicability within the chemical sector (Lu et al., 2020). Wei et al. implemented FTA and HFACS methodologies to investigate the causal relationships inherent in CPEAs. Their findings indicated that FTA is beneficial for analyzing the horizontal logical relationships among causes, while HFACS proves more adept at uncovering the fundamental causes of accidents (Jiang & Han, 2018). Kitagawa's accident causation model identified that societal factors exert a significant influence on accidents. Orbit intersection theory, in articulating the occurrence and progression of accidents, accentuates the interplay and evolution of human trajectories and object trajectories, thereby elucidating the developmental process of accidents (Lu et al., 2020). This theory systematically excavates the underlying causes of accidents and serves as a robust instrument for investigating the origins of accidents (Lu et al., 2020). It has been extensively applied in the analysis of oil explosion incidents, coal mine accidents, and safety production challenges within manufacturing contexts (He & Li, 2025; Lu et al., 2020; Ying & Xuan-Zhe, 2014). CPEAs arise from the interplay of numerous factors, leading to various stages of occurrence and development that are fraught with uncertainties stemming from both internal and external influences (Lu et al., 2020).

3. Safety Measures and Interventions

Effective safety protocols in large-scale construction projects encompass adherence to regulations, the adoption of innovative technologies, and comprehensive workforce training to reduce occupational risks such as falls, electrocution, and ergonomic issues. This section assesses critical interventions by examining their effectiveness and potential for widespread application. By integrating empirical research and case studies, it underscores methods to lower incident rates while tackling obstacles like financial constraints and regulatory inconsistencies, especially in developing countries.

3.1 Regulatory Frameworks and Compliance

Regulatory frameworks, exemplified by OSHA 1926 in the United States and ISO 45001 on an international scale, delineate essential guidelines for the management of hazards in extensive construction endeavors. These standards prescribe practices such as systematic site evaluations, obligatory personal protective equipment (PPE), and tailored safety plans for each site, which have yielded a reduction in incident rates by 20–30% in projects adhering to these regulations (Farina et al., 2013; Molen et al., 2012). In the context of large-scale projects, adherence to these regulations facilitates effective coordination among numerous contractors, thereby diminishing incidents attributable to miscommunication. Nevertheless, the degree of enforcement varies internationally, with developing countries such as Nigeria encountering significant obstacles due to constrained resources and inconsistent oversight (Awodele et al., 2014). Research indicates that rigorous enforcement, in conjunction with sanctions for non-compliance, promotes adherence; however, smaller enterprises frequently encounter difficulties related to the financial burdens of implementation (Simpson & Evens, 2024). Routine audits and certifications, exemplified by ISO 45001's risk-based methodology, further enhance safety outcomes by encouraging proactive identification of hazards. Notwithstanding these advantages, an excessive dependence on regulatory frameworks devoid of technological or behavioral interventions undermines effectiveness, thereby necessitating integrated strategies for scalable enhancements in safety within large-scale construction projects (McCall, 2024; Nawaz & Suleman, 2025).

3.2 Technological Interventions

Technological advancements, encompassing wearable sensors, unmanned aerial vehicles, and artificial intelligence-driven monitoring systems, have significantly revolutionized safety management practices within extensive construction endeavors. Wearable sensors facilitate the real-time detection of ergonomic hazards and falls, thereby diminishing response times by as much as 50% through immediate alerts to supervisory personnel (Glynn et al., 2025; Rane et al., 2023). Unmanned aerial vehicles permit aerial inspections of construction sites, effectively identifying dangers such as precarious scaffolding while safeguarding workers from potential hazards, particularly in high-rise construction projects (Karakhan & Al-Mhdawi, 2024; X. Wang et al., 2025). Building Information Modeling (BIM) augments the identification of hazards during the planning phase, resulting in a 25% reduction of design-related risks in projects such as the stadiums constructed for the Qatar 2022 World Cup. AI-driven analytic tools forecast areas of elevated risk, thus enhancing site coordination. Nonetheless, the elevated costs associated with implementation and requisite training pose significant barriers to adoption, particularly in developing countries with limited financial resources. Despite these obstacles, the scalability of these technologies is improving as costs continue to decline and modular solutions become available. Empirical case studies, such as the implementation of BIM in the Crossrail project, illustrate a reduction in incident rates, highlighting the potential of technology when synergistically integrated with regulatory frameworks and training initiatives to bolster safety in large-scale construction projects (McCall, 2024; Nawaz & Suleman, 2025).

3.3 Training and Behavioral Interventions

Comprehensive safety training and behavioral interventions are pivotal for reducing occupational hazards in large-scale construction. Programs incorporating virtual reality (VR) simulations enhance worker awareness of risks like falls and electrocution, improving hazard recognition by 20% compared to traditional methods (Pereira et al., 2024). Behavioral safety programs, emphasizing peer monitoring and accountability, have lowered injury rates by 15% in large projects by fostering a safety-conscious culture (Olise et al., 2025; Yazdi, 2025). For instance, the London Crossrail project used VR training to simulate high-risk scenarios, reducing errors among multi-contractor teams (HSE, 2023). Training is particularly critical in developing nations, where low literacy and limited safety awareness increase risks (Mccall, 2024; Nawaz & Suleman, 2025).

3.4 Integrated Safety Management Systems

Integrated Safety Management Systems (ISMS) effectively combine risk assessments, regular audits, and ongoing improvements to tackle the complex hazards associated with large-scale construction projects (Aladayleh & Aladaileh, 2024; Frick, 2011; Griffith et al., 2005). A notable example is the London Crossrail initiative, which achieved a remarkable 40% reduction in incidents through proactive safety planning and collaboration among stakeholders (Davies et al., 2014; Lobo & Abid, 2020; McCall, 2024; Nawaz & Suleman, 2025). These systems integrate regulatory compliance, advanced technological tools, and comprehensive training into a unified framework, facilitating dynamic risk management in intricate projects. For instance, risk assessments pinpoint high-hazard areas, while audits verify compliance with standards such as ISO 45001. In large-scale endeavors, ISMS enhances coordination among contractors, leading to a 25% decrease in incidents related to miscommunication (Zou et al., 2007). Nonetheless, challenges in implementation, including significant initial costs and the necessity for skilled personnel, particularly in resource-limited developing nations, persist. Case studies like Qatar 2022 underscore the importance of culturally sensitive systems to accommodate diverse workforces (Hossain, 2025).

4. Conclusion

Large-scale construction projects, vital for global economic growth, expose workers to significant hazards, including falls (36.9–50% of U.S. fatalities), struck-by incidents (10% of accidents), electrocution (9% of fatalities), and ergonomic/chemical risks (BLS, 2024b; Darda'u Rafindadi et al., 2025; Wang et al., 2017). These risks, intensified by operational complexity and inadequate safety measures in developing nations like Nigeria, demand robust interventions (Awodele et al., 2014). Regulatory frameworks, such as OSHA 1926 and ISO 45001, reduce incidents by 20–30%, while technologies like Building Information Modeling (BIM) and wearables enhance hazard detection by up to 50% (Farina et al., 2013; Pereira et al., 2025). Training with virtual reality and integrated safety management systems, as exemplified by Crossrail's 40% incident reduction, further improves outcomes (Davies et al., 2014). However, high implementation costs and inconsistent enforcement, particularly in resource-limited regions, hinder scalability (Awodele et al., 2014). Future research should focus on cost-effective technologies and standardized global regulations to bridge these gaps. This study underscores the need for integrated safety ecosystems to protect workers and enhance efficiency in large-scale construction, providing actionable insights for project managers, policymakers, and safety professionals worldwide.

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