Conceptual Framework for Human Error Causation in High-Risk Construction and Industrial Activities

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Abstract

Human error remains a dominant contributor to accidents and near-miss events in high-risk construction and industrial activities, where complex socio-technical systems, hazardous environments, and time-sensitive operations intersect. This presents a conceptual framework for human error causation that integrates individual, organizational, and system-level determinants to explain how errors emerge, propagate, and result in adverse safety outcomes. Drawing on established theories such as Reason's Swiss Cheese Model, Human Factors Analysis and Classification System (HFACS), and systems engineering perspectives, the framework conceptualizes human error not as isolated unsafe acts, but as the outcome of interacting latent conditions and active failures embedded within project delivery systems. At the individual level, the framework accounts for cognitive limitations, skill-based errors, rule-based mistakes, violations, fatigue, and risk perception, recognizing how stress, workload, and competence shape frontline behavior. At the organizational level, factors such as safety leadership, contractor governance, training adequacy, communication quality, and production pressure are positioned as critical enablers or inhibitors of safe performance. At the system and environmental level, the framework incorporates design complexity, task variability, technological interfaces, regulatory context, and dynamic site conditions that influence human reliability. A key contribution of the framework is its emphasis on feedback loops and coupling effects, illustrating how weak governance, fragmented contractor management, and inadequate learning mechanisms can amplify minor errors into major incidents. The framework also accommodates modern industrial realities, including subcontracting chains, digital safety systems, and automation-assisted work processes, thereby extending traditional human error models to contemporary high-risk project environments. By providing a structured lens for analyzing accident causation, the framework supports proactive hazard identification, targeted safety interventions, and evidence-based policy development. Ultimately, this conceptualization advances safety science by shifting focus from individual blame toward systemic resilience, enabling organizations to design safer work systems and sustainably reduce human error in construction and industrial operations.

Keywords: Human error causation; high-risk construction; industrial safety; systems thinking; contractor safety management; human factors; accident prevention

1. Introduction

High-risk construction and industrial environments remain among the most accident-prone sectors globally, accounting for a disproportionate share of occupational injuries, fatalities, and catastrophic losses (Ayanbode *et al*., 2019). Activities such as heavy civil construction, oil and gas operations, mining, power generation, and large-scale manufacturing routinely involve hazardous energy sources, complex equipment, dynamic work conditions, and tightly coupled tasks (Olamide and Badmus, 2018; Nwafor *et al*., 2019). Despite advances in engineering controls, protective technologies, and regulatory standards, accident statistics across both developed and emerging economies continue to indicate persistent safety challenges (Bankole *et al*., 2019; Ayanbode *et al*., 2019). International labor and safety agencies consistently report that construction and industrial sectors contribute significantly to work-related deaths, with human involvement identified as a dominant factor in accident causation. These trends suggest that technical safeguards alone are insufficient to fully address the underlying drivers of unsafe outcomes in complex, high-risk work systems (Olamide and Badmus, 2019; OSHOMEGIE *et al*., 2019).

Traditional safety management approaches in construction and industrial contexts have largely emphasized technical controls and regulatory compliance. Engineering solutions such as machine guarding, personal protective equipment, and automated safety systems are commonly complemented by prescriptive rules, checklists, and inspection regimes designed to enforce adherence to safety standards (Matter and An, 2017; OSHOMEGIE *et al*., 2019). While these measures are essential, their effectiveness is often constrained by an implicit assumption that accidents result primarily from equipment failure or non-compliance with procedures. Such approaches tend to focus on observable deviations and rule violations, frequently attributing incidents to individual worker error without adequately examining the systemic conditions that shape human behavior (Yeboah and Enow, 2018; Nwafor *et al*., 2019). As a result, safety interventions may become reactive, fragmented, and overly punitive, offering limited insight into why unsafe actions occur repeatedly under similar organizational and operational conditions (Ugwu-Oju *et al*., 2018; Okeke *et al*., 2019)

Growing evidence from safety science and human factors research highlights the limitations of purely technical and compliance-based models in explaining accident causation in complex sociotechnical systems (Orozco, 2019). High-risk construction and industrial activities are characterized by time pressure, production incentives, fragmented subcontracting structures, and constantly changing work environments (Oguntegbe *et al*., 2019; Dako *et al*., 2019). Within these settings, workers and supervisors are required to make rapid decisions under uncertainty, often balancing safety requirements against competing operational demands. Rigid procedural controls may fail to account for variability in real-world conditions, while excessive reliance on compliance can inadvertently encourage rule-bending, normalization of deviance, and underreporting of near misses (Seyi-Lande *et al*., 2018; Odejobi *et al*., 2019). Consequently, accidents frequently emerge not from isolated failures, but from the interaction of latent organizational weaknesses and active human decisions at the operational level (Ahmed and Odejobi, 2018; Michael and Ogunsola, 2019).

In this context, adopting a human error–centered conceptual framework offers a more comprehensive and explanatory approach to safety management. Human error frameworks shift the analytical focus from individual blame to the broader system in which people operate, recognizing that human actions are shaped by task design, organizational culture, leadership practices, technological interfaces, and environmental constraints (NWAFOR *et al*., 2018; Bayeroju *et al*., 2019). By distinguishing between different types of human error such as slips, lapses, mistakes, and violations and by linking these errors to upstream organizational and governance factors, such frameworks enable a deeper understanding of accident causation mechanisms. This perspective aligns with contemporary systems thinking, resilience engineering, and high-reliability organization principles, all of which emphasize anticipation, adaptation, and learning rather than simple rule enforcement (Ugwu-Oju *et al*., 2018; Seyi-Lande *et al*., 2019).

The objective of this conceptual framework is to systematically integrate human, technical, organizational, and environmental factors to explain how errors arise and propagate in high-risk construction and industrial activities. Specifically, the framework seeks to identify key sources of human error, map causal pathways between latent conditions and unsafe acts, and clarify the role of governance, supervision, and safety culture in shaping performance outcomes. The scope of the framework encompasses individual workers, work teams, supervisory structures, and organizational systems across the project lifecycle. By providing a structured lens for analyzing human error causation, the framework aims to support more effective safety interventions, inform policy and regulatory development, and guide future empirical research in construction and industrial safety management.

2. Methodology

The PRISMA methodology was applied to systematically identify, screen, and synthesize empirical and theoretical literature informing the conceptual framework for human error causation in high-risk construction and industrial activities. A comprehensive literature search was conducted across major academic databases, including Scopus, Web of Science, PubMed, IEEE Xplore, and ScienceDirect, to capture multidisciplinary perspectives spanning construction management, industrial safety, human factors engineering, ergonomics, and organizational studies. Search strings combined keywords and Boolean operators related to human error, accident causation, unsafe acts, latent conditions, high-risk industries, construction safety, industrial operations, and systems-based safety models. The search was limited to peer-reviewed journal articles, conference proceedings, and authoritative reports published in English, ensuring relevance and academic rigor.

Following the identification phase, all retrieved records were imported into reference management software, and duplicates were removed. The screening phase involved an initial review of titles and abstracts to exclude studies that were not directly related to human error causation, focused solely on low-risk environments, or lacked relevance to construction or industrial contexts. Studies centered exclusively on technical failure without human or organizational dimensions were also excluded. Full-text eligibility assessment was then conducted for the remaining articles, with inclusion criteria emphasizing explicit discussion of human error mechanisms, contributory factors, or causal models applicable to high-risk operational environments. Both quantitative and qualitative studies were included to capture a broad evidence base, while purely descriptive articles without analytical contribution were excluded.

Data extraction focused on identifying recurring constructs, causal pathways, and explanatory mechanisms related to human error. Key variables extracted included individual-level factors such as cognitive load, fatigue, skill level, and risk perception; task-related factors including work complexity, time pressure, and interface design; and organizational and systemic factors such as safety culture, supervision quality, training systems, communication, and governance structures. Established theoretical models, including the Swiss Cheese Model, Human Factors Analysis and Classification System (HFACS), and sociotechnical systems theory, were critically examined to understand how active failures interact with latent organizational conditions. Particular attention was paid to how contextual pressures in construction and industrial settings—such as subcontracting, dynamic worksites, and production-driven incentives—shape error emergence and propagation.

The synthesis phase followed a narrative and conceptual integration approach rather than meta-analysis, given the

heterogeneity of study designs and outcome measures. Findings were compared and clustered to identify convergent themes and gaps, enabling the development of a coherent conceptual framework that links individual behavior, task design, organizational governance, and external environmental influences. The PRISMA flow process ensured transparency and replicability in study selection, while the structured synthesis strengthened the validity of the proposed framework. This methodology supports the framework's grounding in established evidence and enhances its applicability for analyzing, predicting, and managing human error in high-risk construction and industrial activities.

2.1. Theoretical Foundations of Human Error
Understanding human error in high-risk construction and industrial activities requires a strong theoretical grounding that extends beyond individual behavior to encompass cognitive processes, work system design, and organizational dynamics. Human error has long been recognized as a major contributor to occupational accidents; however, contemporary safety research emphasizes that errors are rarely random or solely attributable to personal negligence (Odejobi and Ahmed, 2018; Ugwu-Oju et al., 2018). Instead, they emerge from predictable interactions between humans, technology, and organizational contexts. The theoretical foundations of human error draw from psychology, human factors and ergonomics (HFE), and safety science, providing a multidimensional lens for explaining why errors occur and how they can be anticipated and managed.

Human error is commonly defined as a deviation from intended or expected performance that can lead to undesirable outcomes. Early safety models treated error as an individual failure, but subsequent research has demonstrated the importance of distinguishing between different types of errors and their underlying causes. A widely accepted classification differentiates between slips, lapses, mistakes, and violations. Slips refer to execution failures, where the intended action is correct but carried out incorrectly, often due to attentional breakdowns or poor interface design. Lapses are memory-related failures, such as forgetting a critical step in a procedure, frequently associated with fatigue, distraction, or high workload. In contrast, mistakes involve failures in planning or decision-making, where the chosen action is inappropriate due to incorrect knowledge, flawed mental models, or misinterpretation of situational cues (Badmus and Olamide, 2018; Okeke et al., 2019). Violations differ from other error types in that they involve deliberate deviations from rules or procedures, often motivated by time pressure, productivity incentives, or perceptions that formal rules are impractical in real working conditions.

Another critical distinction in human error theory is between active failures and latent conditions. Active failures are unsafe acts committed by front-line operators that have immediate and observable consequences, such as incorrect equipment operation or unsafe positioning on a worksite. Latent conditions, however, originate at higher organizational levels and may remain dormant for extended periods before contributing to an accident. These include poor design decisions, inadequate training systems, weak safety leadership, and flawed organizational policies. In high-risk construction and industrial environments, accidents often occur when multiple latent conditions align with active failures, allowing hazards to penetrate existing defenses (Ugwu-Oju et al., 2018; Ekechi, 2019; Ayanbode et al., 2019).

Human error can also be categorized as individual versus system-induced. Individual errors are associated with personal limitations in cognition, perception, or physical capability. System-induced errors, by contrast, arise when the design of tasks, tools, schedules, or organizational processes makes errors more likely, even among competent and well-intentioned workers (Seyi-Lande et al., 2018; Badmus and Olamide, 2019). This distinction underscores the importance of viewing human error not as a moral failing, but as a symptom of deeper system-level weaknesses.

2.2. Human Factors and Ergonomics (HFE) Theory
Human Factors and Ergonomics (HFE) theory provides a foundational framework for analyzing how work systems can be designed to support human capabilities and limitations. HFE encompasses cognitive, physical, and organizational ergonomics, each of which plays a critical role in high-risk construction and industrial settings. Cognitive ergonomics focuses on mental processes such as perception, memory, decision-making, and problem-solving. In complex and dynamic environments, workers must interpret incomplete information, anticipate hazards, and make rapid decisions, often under conditions of uncertainty (Erigha et al., 2019; Anichukwueze et al., 2019). Poorly designed procedures, ambiguous instructions, or complex interfaces can overload cognitive capacity, increasing the likelihood of mistakes.

Physical ergonomics addresses the interaction between human physical characteristics and the work environment, including posture, repetitive movements, and exposure to vibration or noise. In construction and industrial operations, physically demanding tasks, awkward postures, and prolonged manual handling can contribute not only to musculoskeletal injuries but also to fatigue-related errors. Organizational ergonomics extends the analysis to work structures, communication patterns, and management practices, emphasizing how coordination, leadership, and resource allocation influence safety performance (Khandan et al., 2017; Naikar, 2017).

Central to HFE is the concept of human–machine–environment interaction. Modern construction and industrial systems increasingly rely on advanced machinery, automation, and digital technologies. The effectiveness of these systems depends on intuitive interfaces, clear feedback mechanisms, and alignment between human expectations and system behavior. Poorly integrated technologies can create new error pathways, such as automation complacency or mode confusion (Strauch, 2017; Endsley, 2017). Additionally, environmental factors such as weather, lighting, noise, and site congestion can degrade attention and situational awareness, further elevating risk.

Workload, fatigue, attention, and situational awareness are core HFE concepts directly linked to human error. Excessive workload and extended working hours are common in high-risk projects and can impair attention, slow reaction times, and reduce error detection capability. Fatigue, whether physical or cognitive, has been consistently associated with increased accident risk. Situational awareness the ability to perceive, comprehend, and project the state of the environment is particularly critical in dynamic worksites, where loss of awareness can rapidly lead to unsafe decisions and actions (Oshomegie, 2018; Ogunsola et al., 2019).

Safety science and systems thinking provide a broader theoretical context for understanding human error as an emergent property of complex systems. Normal Accident Theory (NAT) posits that in tightly coupled and interactively complex systems, accidents are inevitable due to the unpredictable interactions among system components. In high-risk construction and industrial activities, where multiple tasks, contractors, and technologies interact, NAT highlights the limitations of relying solely on error-free human performance.

In contrast, High Reliability Organization (HRO) theory examines how certain organizations achieve consistently safe performance despite operating in hazardous environments. HRO principles include a preoccupation with failure, reluctance to simplify interpretations, sensitivity to operations, commitment to resilience, and deference to expertise (Ford, 2018; Harvey *et al*., 2019). These principles emphasize continuous learning, open communication, and the empowerment of front-line workers to identify and manage emerging risks.

Resilience engineering further extends systems thinking by focusing on an organization's capacity to anticipate, monitor, respond to, and learn from disturbances. Rather than attempting to eliminate all errors, resilience engineering acknowledges human adaptability as a source of safety, recognizing that successful performance often depends on workers' ability to adjust to variability and unexpected conditions. Together, these theoretical perspectives provide a robust foundation for understanding human error causation and for developing safety frameworks that are proactive, adaptive, and system-oriented.

2.3. Existing Models of Human Error Causation

Understanding human error in high-risk construction and industrial environments has been shaped by several influential theoretical models. These models move beyond simplistic notions of individual failure and instead emphasize systemic, organizational, and sociotechnical contributors to unsafe outcomes. Among the most widely applied are the Swiss Cheese Model, the Human Factors Analysis and Classification System (HFACS), and broader sociotechnical systems models. Together, they provide complementary lenses for analyzing how errors arise and escalate in complex project settings.

The Swiss Cheese Model, developed by James Reason, conceptualizes safety as a series of defensive layers designed to prevent hazards from resulting in harm. Each layer such as regulations, procedures, supervision, and physical safeguards contains inherent weaknesses or "holes" caused by latent conditions and active failures (Mulligan and Bamberger, 2018; Sutton *et al*., 2019). Accidents occur when these holes align, allowing hazards to propagate through all defenses and reach the system's vulnerable points.

In construction and industrial projects, this model is particularly relevant due to the presence of multiple, often fragmented, layers of defense. For example, design reviews, method statements, permit-to-work systems, and on-site supervision are intended to act as barriers against unsafe acts. However, production pressure, inadequate coordination among contractors, or poor enforcement can weaken these barriers. The Swiss Cheese Model effectively illustrates how frontline errors, such as incorrect equipment use, are rarely sufficient on their own to cause accidents; rather, they combine with upstream deficiencies in planning, training, or governance.

The model's strength lies in its ability to shift attention from individual blame to systemic vulnerabilities. Nevertheless, its linear representation of error propagation has been criticized for oversimplifying the dynamic and adaptive nature of modern construction and industrial systems, where defenses may interact in non-linear ways (Wang *et al*., 2017; Adriaensen *et al*., 2019).

HFACS builds on the Swiss Cheese Model by providing a structured taxonomy for categorizing human and organizational factors contributing to accidents. It organizes error causation into four hierarchical levels: unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences. Unsafe acts include errors and violations committed by operators, while preconditions encompass factors such as fatigue, stress, environmental conditions, and team resource management. Supervisory factors address inadequate oversight, inappropriate planning, and failure to correct known problems, and organizational influences include safety culture, resource management, and operational processes.

Originally developed for aviation, HFACS has been widely adapted to construction and industrial contexts. In these environments, unsafe acts may involve deviations from safe work procedures, while preconditions often reflect site congestion, time pressure, and skill mismatches among workers. Supervisory factors are particularly salient in contractor-heavy projects, where unclear authority, weak coordination, and insufficient monitoring can normalize unsafe practices. At the organizational level, cost-driven decision-making, fragmented governance structures, and inconsistent safety policies frequently shape the conditions under which errors occur (Monkelbaan, 2019; Naylor *et al*., 2019).

The adaptability of HFACS is a major advantage, as it allows researchers and practitioners to systematically analyze accident data and identify recurring patterns across projects. However, like the Swiss Cheese Model, HFACS is often applied retrospectively and may underrepresent the dynamic interactions and emergent behaviors characteristic of complex project environments.

Sociotechnical systems models offer a more holistic perspective by emphasizing the interdependence between human, technical, and organizational subsystems. Rather than viewing errors as discrete events, these models conceptualize safety as an emergent property arising from interactions among people, technologies, work processes, and institutional contexts. Human behavior is shaped not only by individual capabilities but also by system design, information flows, and organizational incentives.

In high-risk construction and industrial projects, sociotechnical models are particularly valuable due to the complexity of project ecosystems, which often involve multiple contractors, evolving designs, and dynamic site conditions. Interactions between digital tools, equipment interfaces, organizational routines, and human decision-making can generate emergent risks that are not predictable by analyzing components in isolation (Terziyan *et al*., 2018; Brocal *et al*., 2019). For instance, the introduction of new automation or digital safety platforms may unintentionally increase cognitive workload or create new coordination challenges.

These models highlight the limitations of static, linear approaches to human error causation and support a shift

toward resilience-based safety management. By focusing on system adaptability, feedback loops, and learning mechanisms, sociotechnical perspectives better capture the realities of modern construction and industrial operations. However, their conceptual breadth can make practical application and measurement more challenging.

Collectively, these models provide a robust theoretical foundation for understanding human error causation, while also underscoring the need for integrated, systems-oriented approaches to safety in high-risk project environments.

2.4. Contextual Characteristics of High-Risk Construction and Industrial Activities

High-risk construction and industrial activities are shaped by a set of contextual characteristics that distinguish them from lower-risk operational environments and significantly influence safety performance and human error propensity (Harvey *et al*., 2019; Ryan *et al*., 2019). These contexts are typically marked by complex work environments, fragmented organizational arrangements, and heterogeneous workforce profiles. Understanding these characteristics is essential for explaining why accidents persist despite technical safeguards and for designing effective governance, safety management, and human factors interventions.

Construction and industrial work environments are inherently dynamic and continuously evolving. Unlike fixed manufacturing settings, construction sites change spatially and temporally as projects progress through different phases, such as excavation, structural erection, installation, and commissioning. Each phase introduces new hazards, altered workflows, and shifting interactions between workers, equipment, and materials. This dynamic nature reduces the effectiveness of static risk assessments and increases cognitive demands on workers, who must constantly adapt to unfamiliar layouts, temporary structures, and changing task sequences (Hodgetts *et al*., 2017; Fankhauser, 2017). As a result, situational awareness is frequently degraded, elevating the likelihood of slips, lapses, and decision-making errors.

In addition, high-risk industrial and construction settings routinely involve hazardous materials, heavy machinery, and multiple energy sources, including electrical, mechanical, hydraulic, chemical, and thermal energy. Workers often operate in close proximity to moving equipment, suspended loads, pressurized systems, and hazardous substances. The simultaneous presence of these hazards creates tightly coupled systems where minor deviations can escalate rapidly into serious incidents. Managing such environments requires precise coordination, strict procedural compliance, and reliable communication, yet the complexity of interactions makes complete hazard control difficult (Jain *et al*., 2017; Goble *et al*., 2018). Consequently, human error often emerges not from negligence but from normal performance variability under demanding and hazardous conditions.

The organizational context of high-risk construction and industrial activities is frequently characterized by multi-tier subcontracting arrangements and fragmented accountability. Principal contractors, subcontractors, and sub-subcontractors may operate under separate contractual obligations, management systems, and safety cultures (Ulubeyli *et al*., 2017; Fiocco, 2018). This fragmentation can obscure responsibility for hazard identification, risk control, and safety oversight, leading to gaps in coordination and inconsistent safety practices across organizational boundaries. Workers may receive conflicting instructions or operate under differing safety standards, increasing uncertainty and the potential for unsafe acts.

Time pressure, cost constraints, and productivity-driven incentives further compound these organizational challenges. Construction and industrial projects are often governed by tight schedules, penalty clauses, and competitive bidding processes that prioritize cost efficiency and rapid delivery. Such pressures can encourage risk-taking behaviors, procedural shortcuts, and deferred maintenance or training. At the managerial level, decision-making may favor short-term productivity gains over long-term safety investments, while at the operational level, workers may perceive implicit pressure to complete tasks quickly, even when conditions are unsafe (Pagell *et al*., 2019; Lin *et al*., 2019). These structural incentives shape the context in which human error occurs, transforming organizational priorities into latent conditions that increase accident likelihood.

The workforce in high-risk construction and industrial sectors is typically diverse and heterogeneous, with substantial variability in skill levels, experience, and training. Projects often rely on a mix of highly skilled specialists and less-experienced or temporary workers, creating uneven competence profiles within the same work environment. Training gaps, particularly in hazard recognition and emergency response, can limit workers' ability to anticipate and manage risks effectively. In complex and hazardous settings, such gaps increase reliance on informal practices and peer learning, which may perpetuate unsafe norms.

Cultural, language, and communication barriers are also prevalent, especially in large projects employing migrant or multinational labor. Differences in language proficiency, safety perceptions, and cultural attitudes toward authority can impede effective communication of hazards and procedures. Misunderstandings during task coordination or safety briefings can lead to incorrect assumptions and unsafe actions, even when formal controls are in place.

Finally, contractor mobility and high workforce turnover further undermine safety performance. Short-term contracts and frequent workforce changes reduce organizational learning, weaken safety culture, and limit the effectiveness of continuous improvement initiatives (Bourke and Roper, 2017; Galeazzo *et al*., 2017). Workers with limited attachment to a project or organization may have less access to training and less familiarity with site-specific risks. Together, these workforce characteristics create a context in which human error is not an isolated individual failure but an emergent outcome of complex, unstable, and constrained working conditions.

2.5. Core Components of the Conceptual Framework

The proposed conceptual framework for human error causation in high-risk construction and industrial activities is built around the interaction of multiple system components that collectively shape human performance. Rather than attributing accidents to isolated unsafe acts, the framework integrates individual, task-related, organizational, and environmental factors to explain how errors emerge, propagate, and translate into adverse safety outcomes (Li *et al*., 2017; Bramble, 2017). These components operate simultaneously and dynamically, reinforcing the view that human error is an emergent property of complex sociotechnical systems.

Individual-level factors represent the most immediate contributors to human error, reflecting the cognitive,

psychological, and physical states of workers and supervisors. Cognitive limitations and decision-making biases play a central role in shaping how individuals perceive hazards and select courses of action. In high-risk construction and industrial environments, workers often rely on heuristics and experience-based judgments to cope with time pressure and information overload. While such shortcuts can enhance efficiency, they may also lead to systematic biases such as overconfidence, normalization of deviance, and confirmation bias, increasing the likelihood of unsafe decisions. Errors may occur when mental models fail to accurately reflect evolving site conditions or when individuals misjudge the consequences of their actions.

Fatigue, stress, and physical condition further influence individual performance and error susceptibility. Extended working hours, shift work, physically demanding tasks, and exposure to harsh environmental conditions are common in high-risk projects and can significantly degrade attention, reaction time, and memory. Fatigue has been strongly associated with increased rates of slips, lapses, and procedural omissions, while chronic stress can impair judgment and reduce compliance with safety practices (Wærø et al., 2018; Richardsen et al., 2019). Physical health issues, including dehydration, illness, or musculoskeletal strain, may also contribute to reduced situational awareness and compromised task execution.

Risk perception and safety attitudes shape how individuals interpret and respond to hazards. Workers' perceptions of risk are influenced by prior experience, peer behavior, and organizational norms. In environments where unsafe practices are tolerated or rewarded through productivity incentives, individuals may downplay risks or accept unsafe conditions as normal. Conversely, strong safety attitudes and a belief that management genuinely prioritizes safety can encourage proactive hazard identification and safer decision-making.

Task and technological factors define the immediate work context in which human actions occur and are critical determinants of error likelihood. Task complexity and procedural clarity significantly influence performance in high-risk activities. Complex tasks involving multiple steps, interdependencies, or simultaneous operations increase cognitive load and the potential for mistakes, particularly when procedures are poorly documented or difficult to interpret. Ambiguous or overly rigid procedures may fail to reflect real-world conditions, forcing workers to improvise and increasing the risk of deviations.

Interface design, tools, and equipment usability are central considerations within the conceptual framework. Poorly designed controls, displays, and tools can create confusion, delay responses, and increase the likelihood of slips and misinterpretations. In construction and industrial settings, equipment is often used in challenging conditions involving noise, vibration, dust, and limited visibility, amplifying the importance of intuitive and robust design. Tools and personal protective equipment that are uncomfortable or hinder task performance may also discourage consistent use, indirectly increasing exposure to hazards (Krein et al., 2018; Nill, 2019).

Automation, digital systems, and human–machine coordination represent an increasingly important dimension of task-related factors. Advanced machinery, monitoring systems, and digital safety platforms have the potential to reduce exposure to hazards and enhance situational awareness. However, inadequate integration of automation can introduce new error pathways, such as overreliance on automated alerts, loss of manual skills, or confusion about system status. Effective human–machine coordination requires clear role allocation, transparent system behavior, and training that emphasizes both the capabilities and limitations of automated technologies (Caldwell et al., 2019; Roth et al., 2019).

Organizational and governance factors constitute the upstream conditions that shape individual and task-level performance. Safety leadership and management commitment are consistently identified as critical drivers of safety outcomes in high-risk industries. Leaders influence safety performance through their visible actions, resource allocation decisions, and responses to incidents and near misses. When production pressures are prioritized over safety, or when unsafe practices go unchallenged, latent conditions are created that increase the probability of human error.

Safety policies, procedures, and enforcement mechanisms form the formal structure of safety management systems. While well-designed policies provide essential guidance, their effectiveness depends on consistent implementation and enforcement. Gaps between written procedures and actual practices can undermine credibility and encourage informal workarounds. Excessively punitive enforcement approaches may discourage reporting and learning, whereas balanced systems that emphasize accountability and learning can help identify systemic weaknesses.

Contractor safety governance and oversight mechanisms are particularly important in construction and industrial projects characterized by multi-tier subcontracting and fragmented responsibilities. Inadequate coordination, unclear accountability, and inconsistent safety standards across contractors can create uneven safety performance and elevate error risk. Effective governance requires clear allocation of responsibilities, robust prequalification processes, ongoing monitoring, and integration of contractors into overarching safety management systems (Lingard and Wakefield, 2019; Challender and Whitaker, 2019).

Environmental and external factors provide the broader context within which organizational systems and individual actions are embedded. Weather conditions, site layout, and physical constraints can directly influence human performance by affecting visibility, mobility, and physical comfort. Dynamic worksites with congestion, limited access, or rapidly changing configurations increase the complexity of hazard management and error prevention (Wu et al., 2019; Yan et al., 2019).

Regulatory frameworks and enforcement quality shape organizational behavior and investment in safety systems. Weak enforcement, inconsistent standards, or regulatory gaps may reduce incentives for proactive safety management, while overly prescriptive regulations may limit flexibility and adaptation. Finally, socioeconomic pressures and informal work practices, particularly in emerging economies, can significantly influence human error causation. Job insecurity, informal employment arrangements, and limited access to training may encourage risk-taking and undermine adherence to formal safety controls. Together, these environmental and external factors interact with internal system components to shape the overall risk profile of high-risk construction and industrial activities.

2.6. Error Pathways and Accident Causation Mechanisms

Accidents in high-risk construction and industrial environments rarely result from a single unsafe act. Instead, they emerge through complex error pathways in which latent organizational conditions interact with active human failures, allowing small deviations to accumulate and escalate into serious incidents. Understanding these causation mechanisms is essential for designing effective safety interventions that focus on systemic resilience rather than individual blame.

A central feature of accident causation is the interaction between latent organizational conditions and active human failures. Latent conditions are embedded within the organizational and project context and often originate far from the point of operation. These include inadequate safety governance, poorly defined roles and responsibilities, insufficient training systems, unrealistic schedules, and cost-driven production pressures. Such conditions shape the work environment in which individuals operate, influencing risk perception, decision-making, and compliance with procedures. Active human failures, such as slips, lapses, mistakes, or routine violations, occur at the frontline and are typically the most visible contributors to accidents. However, these failures are frequently symptoms of deeper systemic weaknesses (Woods *et al*., 2017; Richardsen *et al*., 2019). For example, a worker's deviation from a safe work method may reflect ambiguous procedures, inadequate supervision, or conflicting performance incentives rather than deliberate negligence.

Error accumulation and escalation pathways describe how multiple small failures combine over time and across system levels to breach safety defenses. In complex projects, errors often remain latent or inconsequential in isolation, but their effects can compound when they interact with other deficiencies. Minor design inconsistencies, incomplete risk assessments, and informal workarounds may gradually normalize unsafe conditions. As these deviations accumulate, the system's margin of safety erodes, increasing sensitivity to disturbances. Escalation occurs when a triggering event, such as equipment failure or unexpected site conditions, interacts with accumulated errors, leading to rapid loss of control (Pescaroli *et al*., 2017; Sleesman *et al*., 2018). This non-linear progression explains why accidents can appear sudden despite long-standing warning signs and near-miss events.

Supervision and decision authority play a critical role in error containment and escalation prevention. Effective supervision acts as an adaptive control mechanism that detects deviations, reinforces safe practices, and corrects emerging risks before they propagate. Supervisors and managers with clearly defined decision authority can intervene promptly to halt unsafe work, allocate additional resources, or revise plans in response to changing conditions. Conversely, weak or ambiguous supervision can allow unsafe behaviors to persist and become normalized. In contractor-intensive environments, fragmented authority and unclear escalation pathways often delay corrective action, enabling errors to migrate across organizational boundaries. When decision-making is centralized, slow, or detached from operational realities, frontline personnel may resort to informal adaptations that further increase risk exposure (Field *et al*., 2018; Gonzi, 2019).

Feedback loops between incidents, organizational learning, and behavior adaptation are another key mechanism in accident causation. Ideally, incidents and near misses generate feedback that informs learning processes, leading to improved procedures, training, and system design. Such negative feedback loops enhance safety by reducing the likelihood of error recurrence. However, in many construction and industrial contexts, learning mechanisms are weak or poorly integrated. Incident investigations may focus narrowly on individual errors, failing to address underlying organizational contributors. Lessons learned may not be effectively communicated across projects or embedded into operational practice. In some cases, a lack of visible consequences for unsafe behaviors creates positive feedback loops that reinforce risk-taking and procedural drift.

Behavior adaptation also occurs at the individual and team levels, as workers adjust their practices based on experience, perceived norms, and management responses. When organizations consistently prioritize production over safety, adaptive behaviors may improve short-term efficiency while increasing long-term accident risk. Conversely, when leadership reinforces learning, transparency, and just culture principles, adaptive behaviors can enhance system resilience (Boylan and Turner, 2017; Kuntz *et al*., 2017). Understanding these feedback dynamics is therefore essential for interrupting harmful error pathways and fostering sustainable safety performance.

Error pathways in high-risk construction and industrial activities are shaped by dynamic interactions between organizational conditions, human behavior, supervision, and learning processes. Accidents emerge not from isolated failures but from the gradual alignment and escalation of errors across system levels. A comprehensive understanding of these mechanisms supports the development of proactive, governance-oriented safety strategies that strengthen error containment and promote continuous learning.

2.7. Moderating and Mediating Factors

Moderating and mediating factors play a critical role in shaping the relationship between underlying risk conditions and safety outcomes in high-risk construction and industrial activities. Rather than acting as direct causes of accidents, these factors influence how hazards, organizational pressures, and human limitations translate into unsafe acts or resilient performance. Understanding their function is essential for explaining variability in safety performance across projects and for designing interventions that reduce human error and accident likelihood.

Safety culture and safety climate function primarily as moderating variables that influence how individuals and organizations respond to risk. Safety culture reflects the shared values, beliefs, and assumptions regarding the importance of safety, while safety climate represents workers' perceptions of safety priorities at a given point in time. In organizations with a strong safety culture, workers are more likely to comply with procedures, report hazards, and intervene when unsafe conditions are observed (Nævestad *et al*., 2018; Aburumman *et al*., 2019). This moderates the impact of hazardous environments and production pressure by encouraging safer decision-making even under constrained conditions. Conversely, weak safety cultures amplify the effects of risk factors by normalizing deviations, discouraging reporting, and prioritizing productivity over protection. As a result, identical technical hazards may lead to very different outcomes depending on the prevailing safety culture and climate.

Training effectiveness and competency assurance operate largely as mediating mechanisms between workforce

characteristics and safety performance. While many organizations implement training programs, their effectiveness varies considerably in terms of content relevance, delivery quality, and reinforcement through practice. Effective training enhances hazard recognition, procedural knowledge, and adaptive problem-solving, enabling workers to manage complex and dynamic tasks more safely. Competency assurance systems, such as certification, skills verification, and on-the-job assessment, ensure that training translates into actual capability. When these systems are weak or poorly enforced, training becomes a symbolic compliance activity rather than a meaningful risk control, allowing skill gaps to persist (Stafford *et al.*, 2018). In this sense, training quality mediates the relationship between workforce variability and human error by determining whether individual differences result in safe adaptation or unsafe performance.

Communication quality and coordination mechanisms further mediate the translation of organizational complexity into operational risk. High-risk construction and industrial activities require continuous coordination across teams, trades, and organizational boundaries. Clear communication channels, standardized handover processes, and effective supervisory practices reduce ambiguity and align shared mental models of tasks and hazards. High-quality communication enables early detection of deviations and facilitates timely corrective action, thereby interrupting accident pathways. In contrast, fragmented or informal communication increases the likelihood of misunderstandings, conflicting instructions, and uncoordinated actions (Abbas *et al.*, 2018; Bacon, 2018). In multi-contractor environments, weak coordination mechanisms can transform organizational fragmentation into latent conditions that precipitate unsafe acts at the frontline.

Digital safety tools and real-time monitoring systems represent increasingly important moderating and mediating influences in modern high-risk operations. Technologies such as wearable sensors, proximity warning systems, digital permits to work, and real-time analytics platforms enhance visibility of hazards and worker exposure. By providing timely feedback and alerts, these tools can moderate the effects of environmental complexity and human cognitive limitations. At the same time, digital systems mediate safety performance by reshaping decision-making processes, enabling data-driven supervision, and supporting proactive risk management. However, their effectiveness depends on integration with organizational practices and user trust. Poorly implemented digital tools may introduce new forms of complexity or complacency, reducing their intended safety benefits.

Collectively, these moderating and mediating factors highlight that safety outcomes are not solely determined by hazards or individual behavior. Instead, they emerge from interactions between organizational culture, competence development, communication systems, and technological support. Strengthening these factors can attenuate the impact of high-risk contexts and transform human performance from a source of vulnerability into a source of system resilience.

2.8. Outcomes and Consequences

Human error in high-risk construction and industrial activities manifests in a wide range of outcomes and consequences that extend beyond immediate safety incidents to affect project performance and long-term organizational

capability. Understanding these outcomes is essential for appreciating the full impact of human error and for justifying the need for systemic, preventive safety frameworks. The consequences of human error unfold across multiple temporal and organizational levels, from acute injury events to enduring effects on learning, resilience, and organizational reputation.

Immediate safety outcomes represent the most visible and direct consequences of human error. These outcomes include occupational injuries, near misses, and fatalities, each reflecting different points along the accident severity spectrum. Injuries may range from minor, first-aid-level incidents to severe and life-altering harm, depending on the nature of the error and the effectiveness of existing safety barriers. Near misses, while often overlooked, are critical indicators of system vulnerability, revealing situations in which human error occurred but did not result in harm due to chance or last-minute recovery. In high-risk construction and industrial environments, near misses frequently involve hazardous energy releases, equipment malfunctions, or unsafe positioning that could have led to catastrophic outcomes (Purohit *et al.*, 2018; Zhou *et al.*, 2019). Fatalities represent the most severe consequence and often arise from the convergence of multiple latent organizational conditions with active human failures. The prevalence of such outcomes underscores the reality that human error, when unmitigated by robust system defenses, can have irreversible consequences for workers and their families.

Beyond immediate safety impacts, human error exerts significant influence on project-level performance and outcomes. Accidents and serious incidents commonly result in work stoppages, investigations, and regulatory interventions, all of which disrupt project schedules and contribute to delays. In large-scale construction and industrial projects, even a single major incident can trigger cascading effects across interconnected tasks, suppliers, and contractors. Cost overruns frequently accompany these disruptions, driven by medical expenses, compensation claims, equipment damage, legal liabilities, and the need for rework or redesign (Asiedu *et al.*, 2017; Surahyo, 2017). Indirect costs, such as productivity losses, increased insurance premiums, and additional safety compliance requirements, often exceed direct accident-related expenses.

Reputational damage represents another critical project-level consequence of human error. Organizations operating in high-risk sectors are increasingly scrutinized by regulators, clients, investors, and the public, particularly following high-profile accidents. Incidents attributed to human error may be perceived as evidence of weak safety culture or inadequate management oversight, undermining stakeholder trust. For contractors and industrial operators, reputational harm can lead to exclusion from future projects, loss of competitive advantage, and strained relationships with regulators and host communities. In extreme cases, repeated safety failures may threaten an organization's social license to operate, especially in environments where industrial activities have significant social and environmental footprints.

At the organizational level, the long-term consequences of human error are closely linked to learning, adaptation, and resilience. Organizations that respond to incidents through a narrow, blame-focused lens often miss opportunities to identify and address underlying systemic weaknesses. Such approaches may discourage reporting of errors and near misses, reinforcing a cycle of underlearning and repeated

failures. In contrast, organizations that treat human error as a source of information can leverage incidents and near misses to drive continuous improvement. Systematic incident investigation, root cause analysis, and feedback mechanisms enable the identification of latent conditions related to training, design, governance, and resource allocation.

Long-term organizational learning contributes directly to resilience, defined as the capacity to anticipate, absorb, adapt to, and recover from disruptions. In high-risk construction and industrial settings, resilient organizations invest in building adaptive capabilities rather than relying solely on rigid controls. This includes developing strong safety cultures, enhancing communication and coordination across organizational boundaries, and empowering workers to intervene when unsafe conditions arise. Learning from human error also informs the refinement of procedures, redesign of tasks and technologies, and strengthening of contractor governance frameworks.

Ultimately, the outcomes and consequences of human error extend far beyond isolated incidents, shaping the safety performance, economic viability, and sustainability of high-risk construction and industrial operations. Recognizing the multi-level impacts of human error reinforces the importance of conceptual frameworks that integrate immediate safety outcomes with project-level performance and long-term organizational resilience. Such an integrated perspective provides a compelling rationale for moving from reactive accident management toward proactive, system-oriented approaches to human error prevention and control (Ylipää *et al*., 2017; Nojavan *et al*., 2018).

2.9. Framework Implications

The conceptual framework for human error causation in high-risk construction and industrial activities carries significant implications across safety management practice, policy formulation, and future research. By explicitly linking latent organizational conditions, frontline human failures, and systemic interactions, the framework promotes a shift from reactive, blame-focused approaches to proactive, system-oriented strategies that enhance safety performance and organizational resilience.

One of the most immediate implications for safety management is the need to move beyond individual blame and cultivate system-oriented interventions. Traditional safety programs often focus on correcting frontline mistakes through disciplinary measures or retraining. While such approaches may address symptoms, they rarely mitigate the root causes embedded within organizational structures or operational processes. By contrast, the framework encourages safety practitioners to identify latent conditions—such as ambiguous procedures, inadequate supervision, resource constraints, or production pressures—that create the conditions for errors to manifest (Cohen, 2017; Umeokafor *et al*., 2019). Proactive identification and remediation of these latent conditions can prevent error propagation and reduce accident likelihood before incidents occur.

Integration of human factors considerations into routine risk assessments is another critical implication. Recognizing the cognitive, physical, and organizational limitations of workers allows safety managers to design interventions that account for realistic human performance. For instance, workload balancing, fatigue management, and ergonomic task design can reduce error probability, while improved communication

channels and decision support systems facilitate timely reporting of near misses. Collectively, these practices enhance the predictability and reliability of safety outcomes and strengthen organizational learning mechanisms.

At the policy level, the framework underscores the importance of strengthening contractor governance and accountability. Construction and industrial projects often involve complex subcontracting arrangements where safety responsibility is diffuse. By embedding human error causation insights into regulatory frameworks, policymakers can mandate clearer delineation of safety roles, standardized supervision protocols, and robust reporting mechanisms (Kaminski, 2018; Johnson, 2018). Enforcement of these requirements reduces organizational ambiguity and ensures that latent conditions contributing to error are addressed systematically.

Standardization of human factors considerations in safety standards represents a complementary regulatory implication. Current regulations often emphasize physical safeguards and procedural compliance, with limited guidance on cognitive and organizational determinants of error. Incorporating human factors into mandatory safety audits, risk management processes, and certification criteria can elevate the visibility of systemic contributors to accidents and encourage the adoption of evidence-based mitigation strategies across industries.

The framework also presents significant opportunities for empirical research. Validation of causal pathways linking latent organizational conditions, human errors, and incident outcomes remains an important priority. Longitudinal and real-time data collection in construction and industrial contexts can provide quantitative evidence of how errors accumulate, escalate, and interact with supervision and governance mechanisms (Škec *et al*., 2017; Platanou *et al*., 2018). Such empirical insights can inform predictive models and targeted safety interventions.

Cross-industry and cross-cultural comparative studies are another research frontier. Construction practices, regulatory environments, and organizational cultures vary widely, influencing the prevalence and type of latent conditions and human errors. Comparative studies enable researchers to identify universal patterns of error causation as well as context-specific vulnerabilities, supporting the design of adaptable safety frameworks that accommodate diverse operational environments.

Finally, integration with digital governance and safety analytics platforms offers a promising avenue for translating the framework into operational practice. Advanced analytics, sensor networks, and AI-enabled monitoring systems can identify latent conditions, track behavioral deviations, and support evidence-based decision-making in near real-time. By linking theoretical insights with technological capabilities, organizations can operationalize system-oriented safety management and continuously refine interventions based on empirical performance data.

The framework's implications extend across practical, regulatory, and research domains, emphasizing a systemic, human-centered approach to safety. Its adoption can transform safety management from reactive compliance to proactive resilience, enhance contractor accountability, and foster a robust evidence base for improving human reliability in high-risk construction and industrial projects (Feng and Trinh, 2017; Capano and Woo, 2017).

3. Conclusion

The conceptual framework developed for human error causation in high-risk construction and industrial activities integrates individual, task, organizational, and environmental factors to provide a comprehensive understanding of accident emergence. By linking dynamic work environments, multi-tiered organizational structures, and heterogeneous workforce characteristics to both latent conditions and active failures, the framework highlights how errors are not isolated events but emergent outcomes of complex interactions. Moderating and mediating factors such as safety culture, training effectiveness, communication quality, and digital safety tools further shape the translation of risk conditions into unsafe acts, emphasizing that human performance is contingent on organizational and technological contexts as much as on individual capability. This synthesis provides a structured lens for analyzing human error, enabling more precise identification of vulnerabilities and targeted interventions.

The framework contributes to the human error and construction safety literature by bridging traditional individual-centric approaches with systemic perspectives. While earlier research often focused on procedural noncompliance or operator mistakes, this model situates human error within broader organizational, environmental, and contractual contexts. It integrates established theoretical constructs, including the Swiss Cheese Model and sociotechnical systems theory, with empirically observed factors specific to high-risk construction and industrial operations. In doing so, it advances both explanatory and predictive capabilities, offering scholars and practitioners a robust tool for understanding why accidents occur despite technical safeguards and how latent conditions amplify risk.

Adopting a systems-based approach to managing human error provides significant practical value. It encourages organizations to address upstream factors such as work design, organizational alignment, and cultural reinforcement rather than relying solely on reactive measures targeting individual mistakes. By emphasizing interactions across multiple system layers, the framework supports proactive risk management, promotes resilience, and enhances safety outcomes in complex, dynamic, and hazardous operational settings. Ultimately, this approach underscores that effective human error management in high-risk activities requires coordinated attention to people, processes, and technology, providing a strategic foundation for improving safety performance and sustaining operational reliability.

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