



Investigating Integrated Risk Management and Safety Culture Strategies for Enhancing Occupational Health at Construction Sites

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Abstract

The construction industry has consistently been exposed to occupational hazards and work-related accidents due to its dynamic working environments and operational complexities. The present study aimed to investigate integrated risk management and safety culture strategies for enhancing occupational health at construction sites. This quantitative study employed a descriptive-correlational design and involved 382 project managers, engineers, and workers engaged in high-rise construction projects. Data were collected using standardized questionnaires assessing safety, general health, and ergonomics and were analyzed through structural equation modeling (SEM). The findings indicated that safety culture and leadership commitment are critical drivers of the effectiveness of risk management systems. The results demonstrated that integrated risk management, in the absence of a supportive cultural foundation, becomes ineffective due to its reactive and bureaucratic nature. Conversely, safety culture dimensions exerted significant direct effects on improvements in employees' physical and psychological health, with leadership commitment and safety climate playing mediating roles, while effectively reducing accident frequency rates. Within this framework, employees' psychological and cognitive health emerged as a key determinant of reducing human errors and preventing physical injuries. Finally, considering the structural, economic, and contractual barriers prevailing in the construction industry, policy recommendations were proposed regarding revisions to general contractual conditions, the allocation of dedicated and non-discretionary safety budgets, and the transition toward preventive approaches supported by emerging technologies. This study demonstrated that occupational health in construction environments is not merely a technical concern but rather the outcome of synergistic interactions between risk management and organizational culture, the realization of which requires a paradigm shift in overarching project management systems.

Keywords: *Integrated Risk Management, Safety Culture, Occupational Health, Construction Sites*

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1. Introduction

The construction industry is one of the most complex and risk-intensive sectors of the global economy because project activities are performed in dynamic, temporary, and continuously changing work environments in which workers, equipment, materials, subcontractors, and organizational processes interact simultaneously. Unlike relatively stable industrial settings, construction sites are characterized by frequent changes in work location, overlapping operations, variable workforce composition, time pressure, physical exposure, and continuous

modifications to project schedules and execution sequences. These characteristics create a combination of occupational hazards that may include falls from height, struck-by incidents, equipment-related injuries, electrical hazards, excessive physical workload, awkward postures, noise, dust, psychological strain, fatigue, and cognitive overload. Consequently, occupational health and safety cannot be treated as an isolated technical function but must be embedded within the overall project management system. Contemporary project management frameworks similarly emphasize that risk management should be integrated



throughout project planning, execution, monitoring, and control rather than addressed as a separate administrative activity [1]. In construction projects, this integration is particularly important because safety-related risks interact with schedule, cost, quality, human-resource, procurement, and operational risks, meaning that failures in one domain can propagate rapidly across other dimensions of project performance.

Occupational accidents remain one of the most visible indicators of deficiencies in construction risk management. Construction workers frequently encounter hazardous activities involving scaffolding, lifting operations, excavation, temporary electrical systems, powered equipment, confined spaces, manual material handling, and work performed under uncertain environmental conditions. Empirical investigations of occupational accidents have demonstrated that construction incidents often result from a combination of unsafe acts, unsafe conditions, inadequate supervision, insufficient hazard recognition, and weaknesses in organizational controls. Statistical analyses of construction-site accidents have shown that accident patterns cannot be explained solely by immediate worker behavior, because organizational and managerial factors substantially influence both exposure and accident probability [2]. Similarly, cause–consequence modeling of construction accidents has demonstrated that occupational incidents typically emerge from interacting causal chains rather than from a single isolated failure, highlighting the importance of identifying underlying management deficiencies and systemic precursors [3]. These findings support a systems-oriented perspective in which occupational accidents are interpreted as outcomes of interactions among human, technological, environmental, and organizational factors.

Traditional occupational risk management approaches have commonly focused on hazard identification, risk assessment, implementation of engineering or administrative controls, and post-incident corrective action. Although such mechanisms remain essential, their effectiveness may be limited when they are implemented reactively or bureaucratically rather than embedded in everyday managerial decision-making. Job safety analysis, for example, provides a systematic method for breaking work activities into individual tasks, identifying associated hazards, estimating their risk levels, and selecting appropriate control measures. Evidence from occupational settings has demonstrated the utility of structured job safety analysis for prioritizing hazards and directing preventive

interventions [4]. Nevertheless, formal risk assessment alone does not ensure that workers consistently follow preventive procedures, supervisors enforce safety expectations, or managers allocate sufficient organizational resources to safety. Risk management therefore needs to evolve from a compliance-based process toward an integrated managerial system in which technical controls, human behavior, organizational culture, leadership, and real-time information are coordinated.

The concept of integrated risk management is especially relevant to construction because project risks are highly interconnected. Decisions related to project scheduling, resource allocation, subcontractor selection, productivity targets, design modifications, and cost control can directly alter workers' exposure to occupational hazards. Schedule compression, for instance, can increase work intensity, reduce recovery time, encourage simultaneous operations, and create conditions that increase both physical and cognitive risks. Research on construction scheduling optimization has therefore emphasized the need to incorporate multiple project constraints into scheduling decisions rather than treating time optimization as an independent objective [5]. Likewise, optimization-oriented construction management increasingly attempts to balance cost, time, resource utilization, and operational performance through computational techniques. Machine-learning and particle-swarm optimization approaches have demonstrated their capacity to improve predictive modeling and cost optimization in construction project management [6], while genetic algorithm and building information modeling–based approaches have been applied to integrated 5D optimization of project time and cost [7]. Although these advances primarily address project performance, their broader implication is that construction management is increasingly shifting toward integrated, data-driven decision architectures in which safety and occupational health can also be incorporated as optimization criteria.

Building Information Modeling (BIM) has become one of the most influential digital platforms for integrating project information across planning, design, execution, and control stages. BIM facilitates multidimensional visualization, information coordination, clash detection, sequencing, and data sharing among project stakeholders. A bibliometric and science-mapping review of BIM in project management has shown that BIM is increasingly positioned not only as a design technology but also as a comprehensive project-management platform supporting coordination and decision-making [8]. Its integration with machine learning further

expands its potential for predictive analysis and automated risk detection. A systematic review of machine-learning applications to BIM has demonstrated that combining these technologies can support classification, prediction, pattern recognition, automated monitoring, and decision support across construction processes [9]. Accordingly, integrated risk management in modern construction projects can increasingly rely on digital project environments capable of linking occupational hazards to location, work sequence, equipment, worker behavior, and real-time operational information.

Despite the technical potential of digitalization, the successful implementation of innovative safety technologies is conditioned by organizational readiness, cost, infrastructure, personnel competence, and managerial support. Research examining barriers to technology adoption in construction has identified resistance to change, implementation costs, skill limitations, interoperability problems, organizational fragmentation, and uncertainty regarding return on investment as major obstacles to digital transformation [10]. These barriers are particularly significant in occupational safety because many preventive technologies require sustained investment and behavioral adaptation rather than one-time implementation. Consequently, advanced risk-management technologies cannot substitute for a supportive organizational culture. A construction organization may possess sophisticated monitoring equipment, BIM platforms, wearable devices, or artificial-intelligence applications while still exhibiting poor safety performance if workers perceive that production targets are prioritized over safety, supervisors tolerate unsafe behavior, or management commitment to occupational health is inconsistent.

This issue places safety culture and safety climate at the center of occupational health management. Safety culture reflects the shared values, assumptions, norms, beliefs, and organizational practices through which safety is understood and enacted, whereas safety climate generally refers to employees' shared perceptions of organizational policies, practices, and priorities concerning safety. Theoretical developments in safety-climate research have demonstrated that workers interpret managerial decisions, supervisory behaviors, resource allocations, and operational priorities as signals of the organization's genuine commitment to safety [11]. Where productivity pressures systematically override safety requirements, workers may infer that unsafe shortcuts are organizationally acceptable despite formal safety policies. Conversely, visible leadership commitment,

consistent enforcement of standards, open communication, employee participation, non-punitive reporting, and adequate resource allocation can strengthen safety climate and encourage safer behavior. Therefore, safety performance depends not only on the formal existence of risk-management procedures but also on the cultural context within which these procedures are implemented.

Leadership commitment is especially important because project managers and supervisors translate organizational safety policies into daily site practices. Workers continuously observe whether supervisors stop unsafe operations, respond to reported hazards, provide adequate personal protective equipment, allocate time for safety briefings, and avoid penalizing workers for raising concerns. Training is another essential mechanism through which management commitment can be operationalized. Construction safety training has been shown to contribute to improved worker awareness and reductions in occupational accidents by strengthening hazard recognition and reinforcing appropriate safety behaviors [12]. However, training is more effective when it forms part of a broader safety culture rather than functioning as an isolated administrative requirement. If training messages contradict actual managerial priorities, workers may recognize the discrepancy and continue to rely on informal practices. Accordingly, the interaction between training, leadership, safety climate, and risk-management systems should be considered when examining occupational-health outcomes.

Physical occupational health is another central dimension of construction safety because many construction tasks involve strenuous manual labor, repetitive movements, lifting, carrying, bending, kneeling, overhead work, prolonged standing, and exposure to vibration. These conditions substantially increase the risk of musculoskeletal disorders, cumulative trauma, and work-related pain. Ergonomic research among construction workers has demonstrated that awkward working postures and other ergonomic risk factors are significantly associated with musculoskeletal complaints, illustrating the importance of systematic ergonomic assessment in occupational health management [13]. These health problems may reduce work capacity, increase absenteeism, generate lost workdays, and contribute to long-term disability. Integrated risk management should therefore incorporate ergonomic hazards alongside acute accident risks. Focusing exclusively on accident frequency can underestimate the broader health burden associated with chronic physical exposures experienced by construction workers.

Psychological and cognitive health is equally relevant because construction work often involves extended working hours, high responsibility, environmental uncertainty, production pressure, safety-critical decision-making, and continuous exposure to physically demanding conditions. Mental fatigue can reduce vigilance, impair judgment, slow reaction time, and increase the likelihood of human error. Advances in wearable neurophysiological monitoring have begun to provide objective tools for identifying such risks. Deep-learning models using wearable electroencephalography data have demonstrated the feasibility of classifying mental fatigue among construction-equipment operators, highlighting the potential for proactive monitoring of cognitive states that may precede unsafe behavior or operational errors [14]. From an integrated occupational-health perspective, these findings are important because psychological and cognitive health should not be viewed merely as employee well-being outcomes; they are also determinants of hazard perception, situational awareness, decision quality, and accident prevention.

Emerging technologies are increasingly enabling real-time safety surveillance and proactive intervention. Internet of Things (IoT) architectures can integrate wearable devices, environmental sensors, location systems, and communication networks to provide continuous information regarding worker position, exposure conditions, and emergency situations. An IoT-based autonomous safety system for construction sites demonstrated the feasibility of combining real-time alarming, monitoring, and positioning strategies to enhance worker protection [15]. More recently, systematic research on self-powered wearable IoT sensors has highlighted their potential to overcome practical limitations associated with conventional battery-dependent devices while supporting continuous safety monitoring in construction environments [16]. Such technologies can provide risk-management systems with dynamic data, allowing interventions to occur before a hazardous condition develops into an accident.

Computer vision and artificial intelligence have similarly expanded the possibilities for automated construction safety management. Deep-learning-based computer vision can identify unsafe behaviors, recognize missing personal protective equipment, detect hazardous proximity between workers and equipment, and analyze worksite conditions without relying exclusively on manual inspection. Research has demonstrated the potential of computer vision and deep learning to support safety management through automated

identification of construction hazards and unsafe practices [17]. More recent lightweight detection architectures developed for assembly-building environments demonstrate that knowledge distillation and structured pruning can make YOLO-based detection systems more efficient for practical deployment while retaining strong recognition capabilities [18]. These advances suggest that construction safety management is progressing from periodic inspection toward continuous intelligent surveillance, although the effectiveness of such systems still depends on management willingness to act on the information they generate.

Artificial intelligence can also improve organizational learning by extracting patterns from historical accident data. Construction accident reports often contain large quantities of unstructured textual information that are difficult to analyze manually at scale. Convolutional neural network-based automatic text classification has been applied to construction accident reports to categorize accident-related information and support more systematic learning from previous incidents [19]. This capability is particularly important for integrated risk management because accident investigation data can be transformed into predictive knowledge rather than archived solely for regulatory purposes. By identifying recurring patterns across incident narratives, organizations can improve hazard anticipation, training priorities, preventive controls, and managerial decision-making.

At the project-system level, advanced artificial intelligence can further support dynamic resource allocation and risk-sensitive decision-making. Deep reinforcement learning has been applied to dynamic real-time optimization of modular-unit allocation to off-site facilities in post-disaster reconstruction, demonstrating the capacity of AI-based systems to respond adaptively to changing operational conditions [20]. Although such applications extend beyond occupational safety specifically, they illustrate a broader transition toward adaptive construction management in which decisions can be continuously optimized in response to changing project states. This paradigm is directly relevant to safety because construction hazards are likewise dynamic. Risk levels may change within minutes as workers, equipment, materials, weather conditions, and task sequences change. Consequently, static risk assessments performed at the beginning of a project or work shift may not adequately represent emerging hazards.

Nevertheless, technological sophistication cannot eliminate the importance of organizational and human factors. The persistence of construction accidents despite

improvements in equipment, standards, and safety technologies indicates that safety problems frequently arise from the interaction between organizational priorities and frontline conditions. An integrated model should therefore recognize that risk management, safety culture, leadership commitment, physical health, and psychological health are interdependent. Risk-management systems can establish mechanisms for hazard identification and control, but safety culture influences whether these mechanisms are accepted and consistently applied. Leadership commitment converts organizational values into operational decisions, while safety climate shapes workers' perceptions of whether safety requirements are genuine organizational priorities. Physical and psychological health, in turn, affect workers' capacity to perform safely and respond to hazards. This multi-level perspective provides a more comprehensive explanation of construction-site safety than approaches focusing exclusively on accident statistics or technical controls.

Moreover, the temporary and fragmented nature of construction organizations makes the integration of safety management particularly challenging. Construction projects commonly involve multiple contractors, subcontractors, consultants, and temporary workers with different organizational affiliations, employment conditions, safety experiences, and incentive structures. Fragmentation can weaken accountability and produce inconsistencies in safety practices across teams. It can also limit knowledge transfer from one project to another. These problems reinforce the need for integrated managerial mechanisms capable of establishing common safety expectations across contractual and organizational boundaries. Within such systems, risk management should operate not merely as a collection of technical procedures but as an organizational process linked with leadership, communication, workforce participation, training, digital monitoring, and continuous learning.

The accumulated literature therefore points toward a transition from reactive occupational safety toward predictive and preventive safety governance. Traditional systems often respond after hazards, incidents, or injuries have already occurred, whereas contemporary approaches seek to identify leading indicators and intervene before adverse outcomes emerge. Digital monitoring, AI-based recognition, BIM integration, predictive analytics, wearable sensing, and automated accident-report analysis collectively provide important technical foundations for this transition. At the same time, the effectiveness of these technologies depends on organizational culture, leadership commitment, employee acceptance, and appropriate integration with

project-management processes. Evidence regarding occupational hazard assessment [4], construction accident patterns [2], causal modeling of accidents [3], safety climate [11], ergonomics [13], worker training [12], technology-adoption barriers [10], and intelligent monitoring technologies collectively indicates that neither purely technical nor purely behavioral approaches are sufficient in isolation.

Accordingly, a critical research need remains to examine occupational health through a unified framework in which integrated risk management and safety culture are analyzed simultaneously and their direct and indirect relationships with safety climate, leadership commitment, physical health, psychological and cognitive health, and accident reduction are empirically evaluated. Such an approach is particularly necessary in high-rise construction projects, where complex work processes, vertical transportation, work at height, temporary employment, multiple subcontractors, and intense production pressures can amplify both accident risk and occupational-health burdens. Evaluating these constructs within a structural framework can clarify whether formal risk-management systems directly improve health outcomes, whether safety culture strengthens the effectiveness of such systems, and whether safety climate and leadership commitment function as important mechanisms linking organizational safety strategies to workforce health. Therefore, the present study aimed to investigate the integrated strategies of risk management and safety culture and to examine their direct and indirect effects on occupational health, safety climate and leadership commitment, and the reduction of accident and injury rates among personnel working at high-rise construction sites.

2. Methodology

From the perspective of its objectives, the present study was applied research, while in terms of data collection procedures and the nature of the data, it adopted a descriptive-correlational design based on a field survey. The research was conducted using an exclusively quantitative approach at high-rise construction project sites. The statistical population comprised all personnel employed at the decision-making, supervisory, and operational levels of these projects, including project managers, occupational health and safety engineers and supervisors, subcontractors, and permanent, temporary, and seasonal construction workers. According to records maintained by the administrative offices located at the construction sites, the

total population was estimated at approximately 5,200 individuals. Using Cochran's sample size formula with a 5% margin of error and a 95% confidence level, the required sample size was calculated as 358 participants. To account for incomplete responses and potential nonresponse, 400 questionnaires were distributed through proportionate stratified random sampling, with strata defined according to the relative representation of occupational categories across the construction sites. Ultimately, 382 complete and usable questionnaires were collected and included in the final statistical analysis.

The measurement instrument employed in this survey was a standardized, multidimensional, closed-ended questionnaire based on a five-point Likert scale, comprising four sections corresponding to the study variables. These sections included the assessment of risk management mechanisms using a standardized safety management system assessment scale based on the international occupational health and safety management system standard; the evaluation of safety culture and safety climate dimensions through a construction-site version of a standardized safety climate questionnaire; the assessment of musculoskeletal disorders and physical well-being using an ergonomic assessment inventory; and the measurement of burnout, occupational stress, and cognitive health indicators using a burnout inventory and the General Health Questionnaire. In addition to attitudinal measures, numerical data extracted from construction-site health, safety, and environment (HSE) records, including accident frequency rates and lost workdays, were incorporated as supplementary quantitative variables. The face and content validity of the questionnaire were confirmed by an expert panel comprising 10 university academics specializing in construction management and occupational health engineering. The content validity ratio (CVR) ranged from 0.70 to 1.00, while the mean content validity index (CVI) was 0.88. Convergent validity was further established through average variance extracted (AVE) values exceeding 0.53. Instrument reliability was confirmed by Cronbach's alpha coefficients ranging from 0.84 to 0.92 and composite reliability (CR) values exceeding 0.87. Furthermore, research ethics protocols, including obtaining written informed consent and ensuring the complete anonymity of participants' personal information, were rigorously implemented.

Descriptive and inferential statistical techniques were employed using specialized statistical analysis software to process the collected data and empirically test the conceptual model. In the first stage, descriptive statistics, including

frequencies, percentages, means, and standard deviations, were calculated, and tests of normality and multicollinearity were conducted to assess the relevant statistical assumptions. Subsequently, partial least squares structural equation modeling (PLS-SEM) was employed to test the hypothesized relationships and evaluate the structural model. In assessing the measurement model, all indicator factor loadings exceeded 0.70, while discriminant validity was established using the Fornell–Larcker criterion and the heterotrait–monotrait ratio of correlations (HTMT), with all HTMT values below 0.85. Finally, the structural model was evaluated by calculating standardized path coefficients, significance test statistics, coefficients of determination (R^2), effect sizes, and the Stone–Geisser predictive relevance index (Q^2). The direct and indirect effects of risk management strategies and safety culture dimensions on employees' physical and psychological health were statistically examined and confirmed, and the overall goodness of fit of the final model was assessed.

3. Findings and Results

The empirical analysis of data collected from 382 individuals employed at high-rise construction project sites was organized into two levels: descriptive and inferential analysis. First, the demographic characteristics of the participants and the statistical distributions of the principal research variables were examined. Subsequently, partial least squares structural equation modeling (PLS-SEM) was applied to test the research hypotheses, evaluate direct and indirect structural relationships, investigate the mediating roles of the relevant variables, and assess the fit of the final conceptual model.

The demographic analysis revealed that among the 382 participants, 42 individuals (11.0%) were project managers and supervisors, 54 (14.1%) were engineers and occupational health and safety inspectors, 68 (17.8%) were subcontractors and skilled construction tradespeople, and 218 (57.1%) were construction workers. The participants' mean age was 34.6 years ($SD = 7.8$), while their mean construction-site work experience was 8.4 years. Temporary and seasonal contract workers accounted for 63.2% of the construction workforce. The descriptive statistics of the principal constructs, measured on a five-point Likert scale, indicated that integrated risk management ($M = 2.84$) and safety culture ($M = 2.91$) were both below the theoretical midpoint of the scale (3.00), suggesting the predominance of traditional and reactive safety management approaches at

construction sites. In contrast, occupational stress and burnout ($M = 3.62$) and the prevalence of musculoskeletal

pain ($M = 3.78$) exhibited concerning levels above the scale midpoint.

Table 1. Descriptive Statistics, Reliability, and Convergent Validity Indicators of the Research Constructs

Research construct	Mean	Standard deviation	Cronbach's alpha	Composite reliability	Average variance extracted (AVE)
Integrated Risk Management	2.84	0.73	0.884	0.908	0.589
Safety Culture	2.91	0.69	0.912	0.929	0.622
Safety Climate and Leadership Commitment	3.05	0.65	0.871	0.899	0.561
Physical Health (Injury Reduction)	2.68	0.81	0.853	0.887	0.532
Psychological and Cognitive Health	2.54	0.78	0.869	0.898	0.558
Reduction in Accident Frequency Rate	3.11	0.84	0.841	0.880	0.552

To test the structural model and validate the hypothesized relationships, standardized path coefficients and significance test statistics were estimated using a bootstrapping procedure with 5,000 resamples. The structural modeling results indicated that safety culture exerted a positive, direct, and highly significant effect on the effectiveness of integrated risk management. This finding suggests that implementing technical tools and systems for hazard identification and control without a supportive organizational culture may fail to achieve the intended

operational effectiveness. Furthermore, the direct effect of safety culture on improving construction-site safety climate was estimated at $\beta = 0.618$, with a t-statistic of 14.231. Risk management also exerted a direct effect on controlling and reducing accident frequency rates, with a standardized path coefficient of $\beta = 0.382$. However, when safety culture was incorporated alongside risk management, its indirect effect on accident reduction through improved risk management processes was estimated at $\beta = 0.207$, indicating a complementary and integrated structural relationship.

Table 2. Results of Direct and Indirect Hypothesis Testing in the Structural Model

Hypothesized path	Standardized coefficient (β)	Standard deviation	t-statistic	p-value	Hypothesis test result
Safety Culture $\rightarrow$ Integrated Risk Management	0.542	0.046	11.642	< 0.001	Supported
Safety Culture $\rightarrow$ Safety Climate and Leadership Commitment	0.618	0.043	14.231	< 0.001	Supported
Risk Management $\rightarrow$ Reduction in Accident Frequency Rate	0.382	0.057	6.718	< 0.001	Supported
Risk Management $\rightarrow$ Improvement in Physical Health	0.341	0.052	6.557	< 0.001	Supported
Risk Management $\rightarrow$ Improvement in Psychological and Cognitive Health	0.214	0.059	3.627	< 0.001	Supported
Safety Culture $\rightarrow$ Risk Management $\rightarrow$ Accident Reduction	0.207	0.035	5.814	< 0.001	Significant indirect effect
Safety Culture $\rightarrow$ Risk Management $\rightarrow$ Physical Health	0.185	0.032	5.781	< 0.001	Significant indirect effect

The mediation analysis, conducted using bootstrapping and an assessment of the variance accounted for by the mediating effects, demonstrated that safety climate and leadership commitment played a central mediating role in linking safety management strategies to improvements in occupational health outcomes. Specifically, project managers' demonstrable commitment to occupational health standards and the promotion of a non-punitive environment for reporting unsafe conditions indirectly enhanced the effect of risk management on employees' psychological health, increasing the standardized coefficient from a direct

effect of 0.214 to a total combined effect of 0.489. This finding suggests that hazard identification systems, in the absence of supportive leadership behaviors, may be insufficient to alleviate occupational stress and cognitive exhaustion among workers. Similarly, in the domain of physical health and the prevention of musculoskeletal disorders, an active safety climate was associated with greater worker compliance with ergonomic protocols and a significant reduction in accident-related lost workdays. The indirect effect of risk management on physical health

through the mediating role of safety climate was estimated at $\beta = 0.263$ and was statistically highly significant.

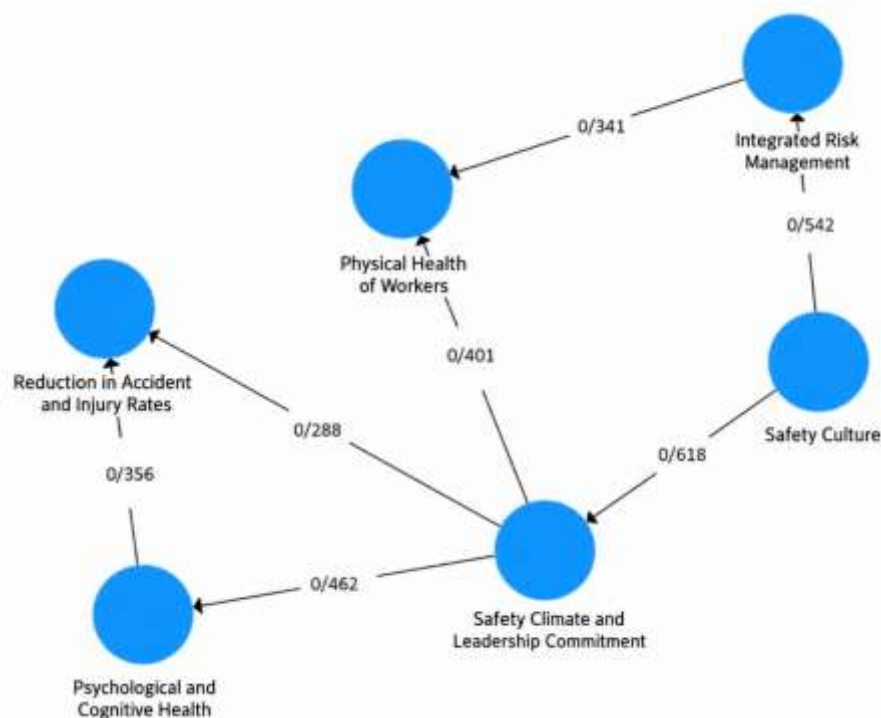


Figure 1. Structural Path Diagram of the Model, Standardized Path Coefficients, and Significance Levels

The assessment of discriminant validity using the Fornell–Larcker criterion indicated that the square root of the average variance extracted for each construct (the values presented along the main diagonal of Table 3) exceeded its bivariate correlations with the other constructs included in the matrix. Furthermore, all heterotrait–monotrait ratio of correlations (HTMT) values were below the critical threshold of 0.85, supporting the conceptual and empirical distinctiveness of the constructs. Regarding the explanatory adequacy of the structural model, the coefficients of determination (R^2) for reduction in accident frequency rate,

physical health, and psychological health were 0.563, 0.512, and 0.487, respectively, indicating moderate to relatively strong explanatory power in the context of behavioral research. Additionally, the Stone–Geisser predictive relevance index (Q^2) yielded positive values exceeding 0.28 for all endogenous constructs, indicating substantial predictive relevance. Finally, the overall goodness-of-fit (GoF) index was calculated at 0.583, suggesting a strong overall fit and a high degree of consistency between the empirical data and the proposed conceptual model.

Table 3. Correlation Matrix of the Research Variables and Assessment of Discriminant Validity Using the Fornell–Larcker Criterion

Variables	1	2	3	4	5	6
1. Integrated Risk Management	(0.767)					
2. Safety Culture	0.542**	(0.788)				
3. Safety Climate and Leadership Commitment	0.481**	0.618**	(0.749)			
4. Physical Health	0.493**	0.421**	0.516**	(0.729)		
5. Psychological and Cognitive Health	0.379**	0.455**	0.543**	0.382**	(0.746)	
6. Reduction in Accident Frequency Rate	0.514**	0.490**	0.488**	0.402**	0.361**	(0.742)

4. Discussion and Conclusion

The present study investigated the integrated role of risk management and safety culture in improving occupational health at high-rise construction sites and demonstrated that occupational safety outcomes are shaped by a combination of technical, organizational, and behavioral mechanisms. The descriptive findings revealed that both integrated risk management and safety culture were below the theoretical midpoint, with mean scores of 2.84 and 2.91, respectively, while occupational stress and burnout and the prevalence of musculoskeletal pain were relatively high. These results suggest that safety management practices in the studied construction environments remain partly reactive and that preventive mechanisms have not yet been fully institutionalized. At the same time, the structural model showed that safety culture significantly predicted integrated risk management, safety climate and leadership commitment played an important mediating role, and integrated risk management significantly contributed to accident reduction as well as improvements in physical and psychological-cognitive health. The coefficients of determination for accident reduction, physical health, and psychological health also indicated that the proposed model explained a substantial proportion of variance in these outcomes. Overall, the findings support the central premise that effective occupational health management in construction requires the simultaneous integration of formal risk-control systems with a supportive safety culture and visible leadership commitment.

One of the most important findings was the significant positive effect of safety culture on integrated risk management, with a standardized path coefficient of $\beta = 0.542$. This result indicates that formal risk-management procedures are more effective when they are embedded within shared organizational norms that prioritize safety, encourage hazard reporting, and reinforce preventive behavior. The finding is strongly consistent with the theoretical proposition that safety climate and culture shape the way employees interpret organizational priorities and determine whether formal safety policies are taken seriously in everyday practice [11]. In environments where workers perceive that productivity, speed, or cost reduction consistently takes precedence over safety, even technically sound risk-management systems may become ceremonial or compliance-oriented. Conversely, when safety is visibly supported by management and integrated into routine

decision-making, formal risk controls are more likely to be implemented consistently. This interpretation is also compatible with the broader project-management perspective that risk processes must be integrated into planning, execution, monitoring, and control rather than treated as isolated administrative functions [1]. The present findings therefore reinforce the view that safety culture constitutes an enabling organizational infrastructure for effective integrated risk management.

The strong direct relationship between safety culture and safety climate and leadership commitment, with $\beta = 0.618$, was another central result. This finding confirms that workers' perceptions of safety are closely tied to the degree to which organizational values are translated into observable managerial actions. Safety culture is not sustained merely through formal policies; rather, it becomes operational through leadership behaviors, communication practices, resource allocation, supervisory consistency, and the credibility of management's response to reported hazards. This interpretation accords with Zohar's conceptualization of safety climate as a collective perception of the priority assigned to safety in organizational practice [11]. The result also aligns with evidence that safety training and managerial reinforcement can improve workers' awareness and reduce occupational accidents when such interventions are integrated into the broader organizational environment [12]. Thus, the present study suggests that leadership commitment acts as a mechanism through which abstract safety values are transformed into concrete expectations and day-to-day behaviors at construction sites.

The findings further showed that integrated risk management had a significant direct effect on reducing accident frequency, with $\beta = 0.382$. This relationship confirms that systematic hazard identification, assessment, prioritization, and control remain essential determinants of safety performance. Construction environments contain multiple interacting hazards, and the probability of incidents increases when these hazards are managed in a fragmented or ad hoc manner. Previous evidence has demonstrated that structured occupational risk-assessment methods, such as job safety analysis, can improve the identification and prioritization of hazardous tasks and facilitate more targeted preventive action [4]. Similarly, retrospective analyses of occupational accidents have shown that construction incidents generally result from interconnected causal chains involving unsafe conditions, insufficient controls, and organizational deficiencies rather than isolated individual errors [3]. Statistical analyses of construction accidents have

likewise emphasized the importance of systemic risk factors and recurrent patterns in accident occurrence [2]. The current result therefore supports the view that integrated risk management can reduce accident frequency by replacing reactive responses with systematic and anticipatory control mechanisms.

The indirect effect of safety culture on accident reduction through integrated risk management, estimated at $\beta = 0.207$, provides further evidence that cultural and technical dimensions of safety are complementary. This finding implies that safety culture does not merely reduce accidents through behavioral compliance or positive attitudes; it also strengthens the effectiveness of formal risk-management processes. A strong safety culture may improve the quality of hazard reporting, increase participation in risk assessments, reduce concealment of unsafe conditions, and encourage adherence to corrective actions. In turn, these behaviors improve the quality and responsiveness of risk-management systems. This integrated interpretation is particularly relevant in complex construction projects, where risk conditions change rapidly and where static procedures may become outdated if they are not supported by continuous frontline communication. The increasing use of digital tools for safety management further underscores this interaction. Automated hazard detection, computer vision, and deep-learning applications can improve the identification of unsafe conditions, but their practical value depends on organizational willingness to respond to the information generated [17]. Likewise, AI-based accident-report classification can enhance organizational learning only when reporting systems are trusted and consistently used [19].

The significant direct effect of risk management on physical health, with $\beta = 0.341$, is also noteworthy. This result indicates that systematic risk management contributes not only to the prevention of acute accidents but also to the reduction of occupational health problems, including musculoskeletal injuries and physical strain. Construction work frequently exposes workers to repetitive movement, heavy lifting, awkward postures, prolonged standing, vibration, and forceful exertion. Ergonomic risk factors of this type have been shown to contribute substantially to musculoskeletal disorders among construction workers [13]. The present findings suggest that when ergonomic hazards are incorporated into risk-management processes rather than treated separately from accident prevention, worker health outcomes can improve. This reinforces the need for occupational risk systems to address both acute and

cumulative hazards. It also indicates that construction organizations should broaden their understanding of safety performance beyond accident counts to include indicators of long-term physical well-being, ergonomic exposure, and lost workdays.

The indirect effect of safety culture on physical health through risk management, with $\beta = 0.185$, adds further support to the integrated model. A safety-oriented culture may increase adherence to ergonomic procedures, encourage proper use of equipment, improve reporting of discomfort and hazardous postures, and facilitate early intervention before minor symptoms progress into disabling conditions. This mechanism is especially plausible in temporary and subcontracted workforces, where workers may otherwise avoid reporting symptoms due to fear of lost income or replacement. By encouraging open communication and emphasizing preventive health rather than only accident reporting, safety culture can improve the practical implementation of ergonomic controls. This result therefore extends the role of safety culture beyond accident prevention and suggests that it is also relevant to broader occupational-health outcomes.

Another important finding concerned psychological and cognitive health. Integrated risk management had a smaller but still significant direct effect on psychological and cognitive health, with $\beta = 0.214$. More importantly, when safety climate and leadership commitment were considered as mediators, the total effect increased substantially to 0.489. This result indicates that formal risk-management procedures alone may have only limited effects on workers' psychological health unless they are accompanied by supportive leadership and a positive safety climate. Construction workers may continue to experience stress, fatigue, and cognitive strain even in technically controlled environments if they perceive supervisors as unsupportive, reporting systems as punitive, or work demands as incompatible with safe performance. The importance of mental and cognitive conditions in construction safety has also been highlighted by research demonstrating that wearable EEG data can be used to classify mental fatigue among construction-equipment operators [14]. Mental fatigue can impair vigilance, hazard recognition, reaction time, and decision-making, thereby increasing both psychological burden and accident risk. The present results therefore support a broader conception of occupational health in which psychological and cognitive well-being are integral elements of safety performance.

The mediating effect of safety climate and leadership commitment on the relationship between risk management and physical health, with an indirect coefficient of $\beta = 0.263$, further demonstrates that leadership is not merely a contextual variable but a mechanism that shapes the effectiveness of formal safety systems. Visible managerial commitment can increase workers' trust in safety procedures, enhance compliance with ergonomic recommendations, and reduce the perception that safety requirements conflict with production goals. Leadership can also influence whether resources are actually provided for safe work, whether hazardous operations are suspended when necessary, and whether workers are encouraged to report unsafe conditions without fear of punishment. This interpretation is consistent with the broader literature on safety climate, which emphasizes that employee perceptions are formed through repeated observations of managerial priorities and actions [11]. Thus, leadership commitment may amplify the benefits of integrated risk management by converting formal procedures into credible and enforceable organizational practices.

The relatively high explanatory power of the model provides additional evidence for the integrated nature of construction occupational health. The R^2 values of 0.563 for accident reduction, 0.512 for physical health, and 0.487 for psychological health indicate that a substantial proportion of the variance in these outcomes was explained by the combined effects of risk management, safety culture, and safety climate. These results are important because construction safety is often examined through fragmented models focusing either on technical controls, worker behavior, or management systems. The present findings suggest that a multidimensional framework provides a more adequate explanation. This interpretation is also compatible with contemporary trends in construction management toward integration of project information, digital technologies, and predictive decision-making. BIM, for example, increasingly supports multidimensional project coordination and can facilitate the integration of safety-related information into project planning and execution [8]. Machine-learning applications to BIM similarly offer opportunities for predictive classification, automated monitoring, and data-driven risk identification [9].

The findings also have implications for the adoption of emerging technologies. Technologies such as IoT sensors, wearable systems, computer vision, and AI-based predictive tools can substantially enhance real-time hazard monitoring, but their effectiveness depends on how they are embedded

within organizational systems. IoT-based autonomous systems can provide real-time alarming, monitoring, and worker-positioning capabilities in construction environments [15], while wearable IoT technologies offer increasing potential for continuous monitoring of workers and environmental conditions [16]. Likewise, advanced object-detection models can support automated recognition of unsafe conditions in construction settings [18]. However, technology adoption in construction is often constrained by organizational resistance, financial limitations, interoperability concerns, and insufficient technical competencies [10]. Therefore, the current findings suggest that investment in technology should occur alongside deliberate efforts to strengthen safety culture and leadership commitment. Otherwise, digital tools may remain underutilized or disconnected from practical decision-making.

The significance of integrated risk management is also consistent with broader developments in optimization-oriented construction management. Contemporary project environments increasingly use computational methods to optimize time, cost, resources, and operational performance. Machine learning combined with particle swarm optimization has demonstrated effectiveness in predictive modeling and cost optimization in construction project management [6], while BIM-integrated genetic algorithms have been applied to optimize project time and cost simultaneously [7]. Construction scheduling research has likewise emphasized the importance of balancing multiple constraints within complex project systems [5]. Deep reinforcement learning has further demonstrated the capacity to support adaptive and real-time resource allocation under dynamic construction conditions [20]. These developments are relevant to safety because they illustrate the feasibility of incorporating occupational-risk criteria into integrated decision models rather than managing safety as a parallel function detached from cost, schedule, and resource decisions.

Taken together, the findings demonstrate that occupational health in high-rise construction projects should be understood as the outcome of interactions among risk-management systems, safety culture, leadership behavior, worker health, and technological support. The relatively low scores for integrated risk management and safety culture, combined with elevated stress, burnout, and musculoskeletal problems, suggest that formal safety systems may not yet be fully embedded in the organizational fabric of construction projects. The structural findings nevertheless show that

when these elements are strengthened, they can significantly improve accident prevention and worker health. Consequently, the study supports a shift from reactive and compliance-centered safety management toward an integrated preventive model in which risk assessment, cultural development, leadership commitment, ergonomics, psychological health, and intelligent technologies are treated as mutually reinforcing components of the same occupational-health system.

The present study has several limitations that should be considered when interpreting its findings. First, the cross-sectional design restricts the ability to establish definitive temporal causality among safety culture, risk management, leadership commitment, and occupational-health outcomes. Second, although the sample included different occupational groups, the study was confined to high-rise construction projects, which may limit the generalizability of the findings to other construction sectors such as infrastructure, road construction, industrial facilities, and small-scale residential projects. Third, a substantial portion of the data was obtained using self-report instruments, creating the possibility of common-method bias, social desirability bias, and subjective differences in the interpretation of safety conditions. Fourth, although objective indicators such as accident frequency and lost workdays were incorporated, the availability and accuracy of site records may vary across contractors. Finally, the proposed model focused on major organizational and health-related variables and did not include potentially influential contextual factors such as project size, ownership structure, contractual arrangements, workforce nationality, shift patterns, economic pressure, or regulatory enforcement intensity.

Future research should examine the proposed relationships using longitudinal, prospective, and multi-level designs that can capture changes in safety culture and occupational-health outcomes over different phases of construction projects. Studies could compare public and private projects, large and small contractors, and different construction sectors to assess the stability of the model across organizational settings. Greater use of objective and continuously collected data is also recommended, including wearable sensor data, physiological indicators, environmental monitoring, digital safety records, near-miss reports, and real-time behavioral observations. Future models could incorporate additional mediators and moderators such as psychological safety, workload, fatigue, safety knowledge, contractor coordination, employment insecurity, digital readiness, and perceived organizational

support. Experimental or quasi-experimental research could also evaluate the effectiveness of targeted interventions designed to strengthen leadership commitment, improve safety climate, or introduce intelligent risk-monitoring technologies. In addition, integrating PLS-SEM with machine-learning techniques could help identify nonlinear relationships and improve the predictive performance of occupational-safety models.

From a practical perspective, construction organizations should move beyond formal compliance and establish integrated occupational-health systems in which safety objectives are explicitly linked to project planning, budgeting, scheduling, procurement, subcontractor management, and performance evaluation. Project managers should receive specific training in safety leadership, and their performance assessments should include measurable indicators of occupational health, incident prevention, hazard reporting, and worker well-being. Dedicated and non-transferable safety budgets should be established to prevent safety expenditures from being reduced under cost pressure. Contractors should create non-punitive reporting systems, conduct routine ergonomic assessments, monitor fatigue and psychological strain, and incorporate leading indicators such as near misses and unsafe-condition reports into management dashboards. Digital technologies should be introduced selectively where they provide clear preventive value, including real-time monitoring, wearable sensing, computer vision, and predictive analytics. Most importantly, these technological and procedural measures should be embedded within a culture in which workers are actively involved in safety decisions and where prevention is treated as a core element of project performance rather than as an administrative requirement.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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