APPLICATION OF HUMAN RELIABILITY ANALYSIS FOR HUMAN ERROR PREVENTION IN ORGANIZATIONS: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Human error remains the dominant cause of safety incidents across various high-risk sectors, including nuclear, energy, mining, manufacturing, and transportation. Human Reliability Analysis (HRA) has evolved into a comprehensive approach for assessing, predicting, and preventing human failure through probabilistic analysis, human-factor evaluation, and organizational condition assessment. This study conducts a systematic literature review (SLR) of 30 relevant scientific articles to map the development of HRA methodologies, identify key determinants of human error, and formulate prevention strategies based on empirical findings. The study selection process follows PRISMA guidelines and is supported by bibliometric analysis using VOSviewer. The findings reveal that modern HRA methods—such as Bayesian HRA, fuzzy HRA, Monte Carlo simulation, FRAM–CREAM, and Dynamic HRA—are more capable of capturing operator variability, expert-judgment uncertainties, and dynamic work conditions compared with classical deterministic models. Furthermore, individual factors (mental workload, situational awareness, experience), organizational factors (safety leadership, safety culture, coordination quality), and task factors (procedure complexity, time pressure, environmental conditions) interact strongly in shaping the likelihood of human error. The implementation of HRA has proven beneficial for organizations by enabling the redesign of work procedures, enhancing training programs, simplifying human–machine interfaces, and prioritizing interventions at the most critical risk points. Overall, this study reinforces that HRA is a strategic tool that must be integrated into modern safety-management systems to strengthen human-error prevention and improve organizational reliability.

Keywords: *Human Reliability Analysis; Human Error; Probability Assessment; Performance Shaping Factors; Bayesian HRA; Fuzzy HRA; Dynamic HRA; Sistem Keselamatan; Organisasi Berisiko Tinggi; Systematic Literature Review.*

INTRODUCTION

Human Reliability Analysis (HRA) has evolved as a critical approach for understanding human contributions to system failures, particularly in high-risk work environments. Across sectors such as nuclear, chemical, manufacturing, and transportation, human error remains the dominant cause of safety incidents, prompting organizations to adopt quantitative methods for assessing and controlling the likelihood of such failures. HRA provides a structured framework for identifying critical tasks, analyzing contextual factors, and systematically estimating Human Error Probability (HEP) (Greco et al., 2021). The increasing complexity of modern systems further strengthens the need for data-driven approaches, especially as organizations face growing demands for greater accuracy in predicting human-error risks.

Research developments indicate that human error is influenced not only by the type of task but also by variations in actual working conditions and differences in individual or team characteristics. International empirical studies and long-term simulator datasets such as SACADA and HuREX demonstrate that factors such as information quality, time pressure, interface design, and team coordination styles generate significant variability in human performance (Park et al., 2022) and (Jung et al., 2024). This variability underscores the need for HRA models capable of capturing real-world uncertainty rather than relying solely on average values, which often introduce bias or overconfidence.

Contemporary HRA approaches increasingly incorporate advanced statistical methods to strengthen the empirical foundations of human-failure probability assessments. Bayesian models, for example, have proven effective in integrating simulator data, accounting for scenario-to-scenario variability as well as crew-to-crew variability, thereby producing more realistic HEP estimates (Greco et al., 2021) and (Y. Kim et al., 2023). Additionally, research indicates that combining empirical data with more modern task taxonomies can enhance the accuracy of HEP calculations and support more defensible risk-informed decision-making.

Despite significant advancements in HRA research, systematic syntheses that examine its application as a mechanism for preventing human error remain relatively limited. Therefore, this study employs a Systematic Literature Review (SLR) to organize empirical findings, identify the dominant methods used, and summarize HRA implementation practices across various sectors. By reviewing articles that meet PRISMA criteria and conducting bibliometric mapping using VOSviewer, this study provides a comprehensive overview of the strategic role of HRA in strengthening organizational safety and reliability.

METHODOLOGY

This study employs a systematic literature review (SLR) approach to examine in depth how human reliability analysis (HRA) is applied as a strategy for preventing human error across various types of organizations. The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021) to ensure that the literature-selection process is systematic, transparent, replicable, and scientifically valid. The literature search was conducted using three major academic databases: Scopus, Google Scholar, and ScienceDirect. The keywords used included human reliability analysis, human error, HEP estimation, performance shaping factors, Bayesian HRA, organizational factors and human reliability, PSA human factors, and accident prevention. The inclusion criteria for journal selection were as follows: (a) articles written in English or Indonesian and published between 2020 and 2025; (b) articles discussing the application of HRA, Human Error Probability (HEP) measurement, human factors, organizational factors, or error-prevention strategies; (c) peer-reviewed scientific journal articles, including empirical studies, HRA model developments, or relevant conceptual reviews; and (d) availability in full-text format. Meanwhile, the exclusion criteria included articles that discussed general safety without an HRA approach, articles lacking clear methods or results, and duplicate publications.

Data synthesis was conducted by categorizing key findings from each article, such as the types of HRA methods used (THERP, SPAR-H, CREAM, Bayesian HRA, fuzzy-HRA), factors influencing human error, and forms of organizational interventions proven effective in preventing human error. Each article was compared to identify patterns, differences, and emerging thematic trends over the past five years. In addition, bibliometric mapping using VOSviewer was employed to trace relationships among keywords and visually identify research trends in HRA. The process of searching, screening, and selecting articles is presented in Figure 1, following the PRISMA 2020 guidelines.

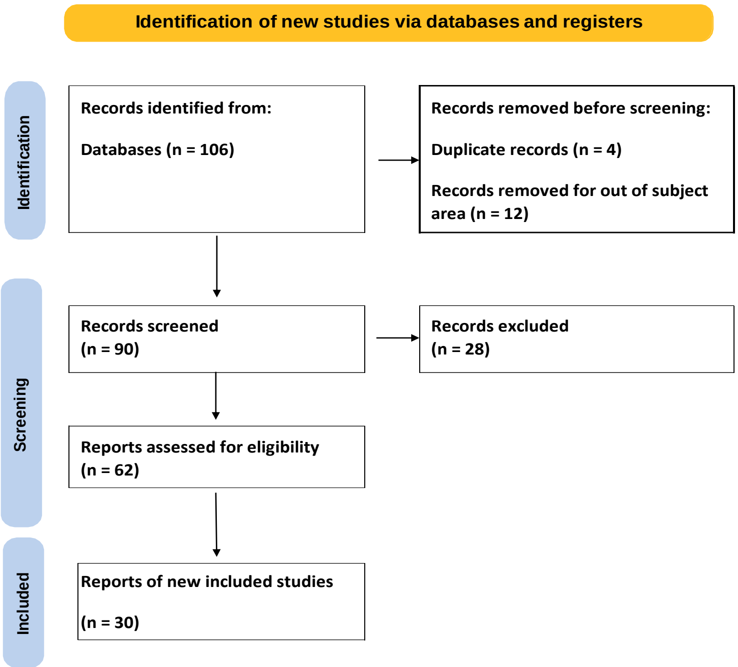

Figure 1. PRISMA 2020 Flow Diagram of the Literature Search Process.

RESULTS AND DISCUSSION

Results

The author conducted an initial analysis using the VOSviewer application as a supporting tool during the screening and preliminary literature review process. This application was used to identify relationships among keywords, evaluate the alignment of articles with the study's scope, and ensure their relevance to the research questions. Based on the VOSviewer visualization results, the most dominant and closely interconnected keywords were human reliability analysis, human error, performance shaping factors, organizational factors and human reliability, and PSA human factors. The visualization presented in the figure below shows that the application of Human Reliability Analysis for preventing human error in organizations remains a highly relevant and continuously evolving area of research.

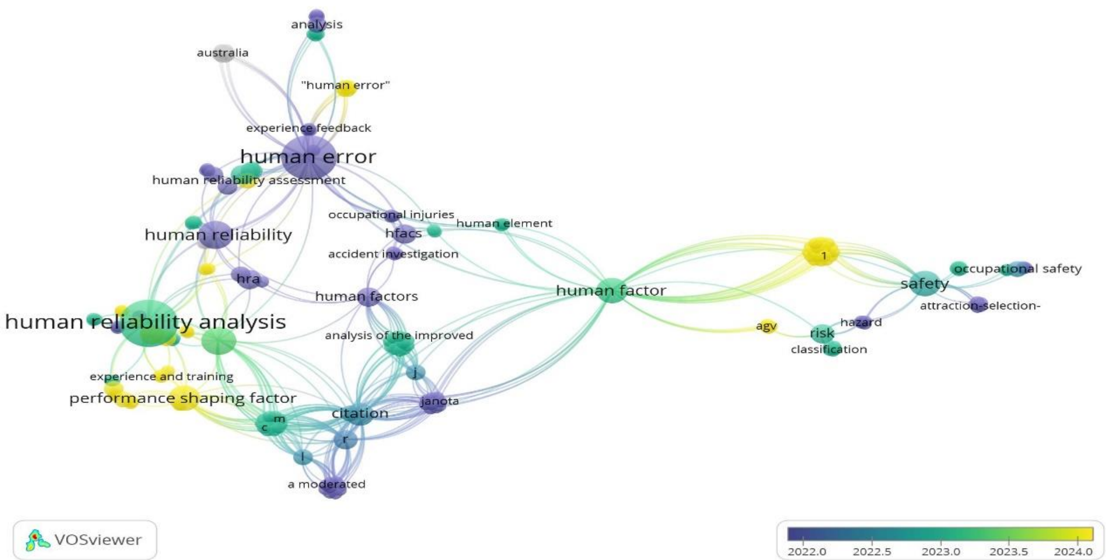

Figure 2. Visualization results generated using the VOSviewer application

The results of the reviewed journal articles are presented in Table 1 below

Table 1. Reviewed Journal Articles.

Author, Year, and Country	Research Objective	Sample	Key Findings
Aghaei et al., 2021 – Iran	To develop the Z-HEART method for analyzing human error in power-system de-energization procedures.	De-energization procedures in an Iranian electric-power company.	Z-HEART produces more realistic HEP values because it incorporates uncertainty and variability in operator performance.
Alencer et al., 2025 – Brazil	To integrate FRAM and fuzzy-CREAM for analyzing human error in underground mining operations.	Loader operators and haul-truck drivers in an underground mining site.	The FRAM–fuzzy CREAM combination successfully identifies critical interactions between task variability and environmental conditions contributing to human error.
Ali Reza Zaker Hossein et al., 2024 – Iran	To estimate the probability of human error in maintenance activities using a refined human-factors model.	Maintenance technicians servicing mining trucks at the Golgohar Iron Ore Complex.	Mental workload, inadequate information, and high task demands were found to be the most influential factors affecting human error.
Bussier & Chong, 2022 – Australia	To analyze relationships between safety measures, psychological distress, and human error in construction settings.	Australian construction workers; psychological-distress survey and safety-performance assessment.	Psychological distress significantly increases the likelihood of human error and negatively affects workers' safety performance.
Ciani et al., 2021 – Italy	To propose a fuzzy-logic-based HRA framework to address expert subjectivity in HEP estimation.	Expert assessors from safety and risk-analysis domains.	Fuzzy logic improves the flexibility and robustness of HEP estimation compared with traditional deterministic methods.
Greco, Podofillini & Dang, 2021 – Swiss (PSI, Switzerland)	To develop a Bayesian hierarchical model capable of processing long-term human-performance datasets for HRA applications.	Crew-performance data from SACADA and other long-term human-reliability data-collection programs at PSI.	The hierarchical Bayesian model generates more realistic and data-driven HEP estimates by capturing inter-scenario variability and crew-to-crew performance differences.
Guglielmi et al., 2022 – Italy	To design an integrated HRA model that incorporates organizational, team, and environmental factors in logistics-hub operations.	Case study conducted in a logistics hub operated by a multinational distribution company.	Human-factor elements such as communication, safety culture, situational awareness, and workload significantly affect operational reliability.
Hamza & Diaconeasa, 2022 – United States	To propose a structured framework for applying HRA in the early phases of the Probabilistic Risk Assessment (PRA) of the Xe-100 modular reactor.	PRA modeling of the Xe-100 reactor and corresponding accident-progression scenarios.	The framework effectively identifies critical operator actions influencing accident progression, improving early-stage reactor safety analysis.
Hung & Dai, 2024 – Taiwan	To evaluate human error in semiconductor-	Semiconductor fabrication	Time pressure, mental workload, and environmental

	manufacturing tasks using an enhanced performance-shaping-factor model.	technicians performing high-precision operational tasks.	instability were found to be the strongest predictors of operator error in semiconductor facilities.
Jiang et al., 2022 – China	To assess HRA applicability in coal-mine operations using an improved CREAM-based approach.	Underground coal-mine workers performing hazardous operational activities.	The improved CREAM model more accurately captures contextual variability, revealing that inadequate information flow and high physical demands are the primary drivers of human error.
Jung, Kim & Park, 2024 – South Korea	To develop a new time-reliability correlation (TRC) model for diagnostic error probability in nuclear power plants (NPPs) with modern human–machine interfaces (HMI), and to compare it with the classical THERP TRC.	Diagnostic-time data from the Korean reference NPP simulator equipped with a modern digital HMI.	The new TRC shows that the median THERP TRC remains conservative up to around 25 minutes but becomes overly optimistic for longer diagnostic times; adjustments are needed to align TRC models with modern operational environments.
Kim et al., 2024 – South Korea	To develop the SAM-L2HRA method for Level-2 PSA HRA using table-top exercises based on Severe Accident Management Guidelines (SAMG).	Severe accident scenarios (ELAP/LUHS) and TTX exercises with NPP operators.	The TTX revealed that SAMG tasks are complex, highly decision-intensive, and strongly prone to error; the SAM-L2HRA approach enhances human-error modeling during severe-accident conditions.
Kim, Kim & Park, 2023 – South Korea	To propose a data-informed dependency assessment method for calculating conditional probabilities of successor human failure events based on quantitative evidence of dependency between HFEs.	HRA data from empirical studies, insufficient time-based statistical functions, and a sequence-alignment algorithm applied to accident-event sequences.	Six dependency features were evaluated and combined into an arithmetic expression; the new method produces more justifiable conditional-failure estimates than classical THERP and highlights the importance of data-driven dependency modeling.
La Fata, Giallanza, Adelfio, Micale & La Scalia, 2023 – Italy	To identify interrelationships among Performance Shaping Factors (PSFs) and determine the most influential PSFs affecting human error using MCDM methods (DEMATEL & ANP).	An automated pistachio-production agri-food company; human-factor analysis of production-line workers.	PSFs influence one another and are not independent. The most influential PSFs are *procedures* and *fitness for duty*, while the most impacted are *complexity* and *work processes*. Procedural factors, stress, and ergonomics were dominant in determining human reliability.
Liinasuo et al., 2020 – Finland	To conduct a comprehensive review of Dynamic HRA	International literature on Dynamic HRA,	Dynamic HRA evaluates errors contextually and dynamically; it incorporates

	development and its application in modern digital control rooms.	hybrid control rooms, and digital HMIs.	situational changes, real-time PSFs, and human–machine interactions that traditional HRA models fail to capture.
Lu et al., 2023 – China	To develop a VACP-based mental-overload assessment method that incorporates PSF influences and models overload probability using a Bayesian Network.	Maryland helicopter accident case; task data, PSFs, and operator-performance information.	PSFs were found to increase mental workload and reduce operator capacity; the Bayesian Network predicted mental overload more accurately than traditional methods, making it more effective for preventing cognitive errors.
Mohammadfam et al., 2022 – Iran (Mining)	To identify and analyze factors affecting human reliability in open-pit mine design using the Fuzzy Delphi and DEMATEL methods.	Expert panel from occupational safety and mining engineering fields in Iran; 19 final variables analyzed as causes or effects.	Root causes of design-related errors include weak organizational management, poor resource allocation, inadequate training, and lack of experience; fatigue, depression, and low motivation emerged as effect variables. The findings provide a foundation for developing design-error control strategies in mining.
Neves et al., 2024 – Portugal	To examine how organizational and human factors influence the reliability of railway-transport workers through SPAD incident analysis.	SPAD data from Portuguese train drivers; survey on organizational factors and work experience.	Age, experience, supervision quality, and safety culture significantly influence SPAD occurrences; improvements in organizational factors consistently reduce human-error rates.
Niu & Zhao, 2022 – China	To investigate how safety attitudes influence human error among coal-mine workers in smart-mining contexts, and to test the mediating role of situational awareness and the moderating effect of task complexity.	246 full-time coal-mine workers in a smart-mining environment; data collected in two waves (time-lagged).	Safety attitude significantly decreases human error. Situational awareness is a strong mediator explaining how safety attitude shapes behavior. Task complexity strengthens the effect of safety attitude on situational awareness. The moderated-mediation model was statistically significant.
Park & Boring, 2025 – United States	To develop a Dynamic HRA model based on the EMRALD platform to simulate the evolution of human error during extended ELAP accident scenarios in NPPs.	ELAP (extended loss of AC power) scenarios in a PWR; cognitive simulations and operational data.	EMRALD captures time-varying PSF changes; Dynamic HRA more accurately reflects real operator conditions during accidents compared with static HRA methods.
Park et al., 2022 – United States & South Korea	To develop the SHEEP (Simplified Human Error Experimental Program) framework for	Experiments using the *Rancor Microworld* with student participants,	Data from simplified simulators can provide meaningful error patterns and relevant PSF information that

	collecting HRA data using a simplified simulator and student operators as a complementary dataset to full-scope studies.	compared with actual operator data from the HuREX study.	support full-scope studies, although differences exist between student participants and licensed operators.
Podofillini, Reer & Dang, 2023 – Switzerland	To develop a traceable process for constructing Bayesian Belief Network (BBN) HRA models using limited data and expert judgment, with application to errors of commission (EOC).	Retrospective operational-event data containing EOCs, supplemented by expert evaluations of triggering factors.	The combination of functional interpolation and Bayesian updating produces transparent and updatable BBNs that can incorporate new data and provide a more systematic way to quantify EOC probabilities within PSA.
Porthin, Liinasuo & Kling, 2020 – Finland	To analyze the impact of digitalized control rooms (digital HSI) on Human Reliability Analysis (HRA), including changes in PSFs and the emergence of new error mechanisms in Advanced Control Rooms (ACRs).	Literature review covering multiple studies of digital HSI in NPPs; evaluation of analog vs. digital control-room systems.	Digitalization increases operator information but introduces interface-management tasks, potential mode confusion, high cognitive workload, and reduced team communication. Traditional PSFs remain relevant but require redefinition in digital contexts. Training, experience, procedure quality, and task complexity are key factors affecting HEP.
Riyadi & Winarno, 2023 – Indonesia	To identify the causes of occupational accidents using SHERPA and HEART in the packaging industry.	Accident data and task-analysis documents from a packaging company.	Tasks 1 and 5 show the highest HEP (0.928); dominant causes include PPE negligence and procedural violations. Recommendations include discipline reinforcement and safety-protocol socialization.
Vechgama et al., 2024 – South Korea & Thailand	To develop an HRA framework for estimating nominal Human Error Probability for the TRIGA research reactor in Thailand using EMBRACE, HuREX, and TACOM tools.	TRIGA emergency-procedure documents, HuREX data, and HRA assessments from KAERI and TINT practitioners regarding operator actions.	The proposed HRA framework effectively classifies error types, improves emergency operating procedures, and identifies nominal human errors most critical to the TRIGA reactor's risk profile.
Vechgama et al., 2025 – Thailand / South Korea	To develop TRIGA-specific Performance Shaping Factors (PSFs) using the EMBRACE framework and expert elicitation.	TRR-1/M1 reactor operators; PSF surveys and cognitive analyses of EOO/EOC.	The new PSF model provides a more accurate representation of HEP in research reactors; integrating expert elicitation improves the reliability of PSFs used within the TRIGA HRA framework.

Wang et al., 2021 – China	To analyze the behavioral reliability of coal-mine operators in noisy environments using a Monte Carlo–based approach.	Underground coal-mine operators; physiological experiments and reliability modeling.	High noise levels (≥90 dB) decrease behavioral reliability and increase accident risk; the Monte Carlo model effectively predicts human-error probabilities in extreme-noise conditions.
Yang et al., 2024 – Italy & China (Process Industry)	To develop a data-driven Causal Bayesian Network to model management and organizational factors (MOFs) contributing to human error in process industries.	Process-accident data from the EU eMARS database containing incidents influenced by human and organizational factors.	The BN model shows that human–machine system reliability is highly sensitive to organizational factors such as training adequacy and procedural quality; the model can quantify MOF contributions to system reliability.
Zgair et al., 2023 – Malaysia / Iraq	To conduct a systematic literature review on how workplace-safety practices influence individual and organizational outcomes.	70 articles (2010–2021) across multiple sectors.	Safety leadership, safety culture, and TQM were the most influential factors in improving safe behavior and reducing human error; safety performance is directly linked to employee commitment and organizational outcomes.
Zhang et al., 2021 – China	To propose a new dependence-assessment method in HRA using linguistic hesitant fuzzy sets combined with THERP.	Healthcare-sector case study; dependency analysis among Human Failure Events.	The proposed method captures expert-judgment uncertainty better than classical THERP and produces more stable and realistic HFE-dependency assessments.

DISCUSSION

General Patterns in the Application of Human Reliability Analysis (HRA) within Organizations

A synthesis of the 30 reviewed articles shows that the application of HRA has advanced rapidly across high-risk organizations such as nuclear power, energy, transportation, mining, and manufacturing. In the nuclear sector, Greco et al. (2021) demonstrate that hierarchical Bayesian models enhance a system's ability to capture crew-to-crew variability, while Podofillini et al. (2023) developed a traceable and updateable Bayesian-network process that enables more realistic error analysis. Research by Kim et al. (2023) shows that dependencies among Human Failure Events (HFEs) can be analyzed using a data-informed dependency approach, whereas Park et al. (2022) found that simplified simulators such as SHEEP can improve the quality of HRA datasets. Hamza and Diaconeasa (2022) emphasize that integrating HRA during the early reactor-design phase can reduce operator actions that do not contribute to safety, and Jung et al. (2024) updated time-reliability correlations to better reflect modern digital HMI systems, which no longer align with classical THERP-based models.

In the process and energy industries, Yang et al. (2024) show that causal Bayesian networks are effective in mapping the influence of managerial and organizational factors on human reliability. In the mining sector, Dantas et al. (2025) combined FRAM and fuzzy CREAM to characterize critical work functions in underground mining operations, while Mohammadfam et al. (2022) identified the root causes of design errors in open-pit mine planning using the Fuzzy Delphi and DEMATEL methods. In the railway transportation sector, Ciani et al. (2021) employed fuzzy HRA to reduce expert-judgment bias, and Neves et al. (2024) demonstrated that age, experience, and supervision quality significantly contribute to SPAD occurrences.

In maintenance operations, Aghaei et al. (2021) developed Z-HEART and adapted fuzzy HEART to produce more accurate HEP estimations. In chemical-emergency response contexts, Jiang et al. (2022) identified that initial handling and site cleanup pose the highest error risks. Riyadi (2023) mapped potential errors in maritime SAR helicopter-hoist operations using SHERPA, while in the Indonesian industrial context, Riyadi and Winarno (2023) found the highest HEP values in procedure-verification activities. Psychological factors also emerged as key determinants, as demonstrated by Bussier and Chong (2022), who showed that psychological distress significantly increases human-error risk during high-altitude work. Zgair et al. (2023) emphasized that safety leadership and TQM are critical determinants of safe behavior, whereas Guglielmi et al. (2022) introduced the concept of human barriers to enhance operator reliability. In the cognitive domain, Lu et al. (2023) modeled operator mental workload using VACP and Bayesian Networks, while Wang et al. (2021) predicted underground-mine operator behavioral reliability through Monte Carlo simulation. For the TRIGA research reactor, Vechgama et al. (2025) adapted PSFs and HEP values specifically to the facility's operational characteristics. The direction of dynamic-HRA research is further strengthened by Kling, (2020) and Park & Boring, (2025) who demonstrated that evolving operational conditions produce dynamic changes in error estimations.

Determinant Factors of Human Error Across Industrial Contexts

A comprehensive review of the 30 articles reveals three major groups of error determinants: individual factors, organizational factors, and task-related factors. From the individual perspective, Wang et al. (2021) demonstrated that extreme noise significantly reduces the behavioral reliability of underground mine operators, while Fata et al., (2023) explained that specific combinations of PSFs increase mental overload and reduce diagnostic accuracy during helicopter-accident simulations. Niu & Zhao, (2022) found that safety attitudes mediate the relationship between task complexity and human error, particularly in technology-intensive coal-mining environments. Hung and Dai (2024) further showed that errors in SAR operations frequently stem from poor situational awareness and communication failures.

Organizational factors emerged as highly influential determinants. Mohammadfam et al. (2022) emphasized that weak management, inadequate resource allocation, and insufficient training constitute the root causes of design errors in mining operations. Safety leadership, mental workload, and operational communication consistently appear as strong predictors of human reliability. Neves et al. (2024) added that poor supervision and inadequate training significantly increase SPAD probability in railway operations. Zgair et al. (2023) demonstrated that TQM and safety culture enhance safe behavior across industries, while Guglielmi et al. (2022) conceptualized human barriers as structural layers that shield organizations from error.

Task-related and environmental aspects also play a significant role. Jiang et al. (2022) provided evidence that the initial handling and site-cleanup stages in chemical-accident response are the most error-prone activities. Riyadi and Winarno (2023) found that negligence in PPE use and violations of standard operating procedures generate the highest HEP values in the packaging industry. Hung and Dai (2024) identified numerous error points in helicopter-hoist operations, while Bussier and Chong (2022) showed that workers performing high-altitude tasks are highly sensitive to psychological conditions. Ciani et al. (2021) highlighted that complex procedures within railway systems increase operator-assessment uncertainty. Dantas et al. (2025) further demonstrated that variability in critical work functions leads to substantial fluctuations in error rates in underground mining operations.

The Transformation of HRA Methods Toward More Accurate and Adaptive Models

The evolution of Human Reliability Analysis (HRA) over the past three decades, as reflected in the 30 reviewed articles, reveals a fundamental shift from deterministic approaches toward data-driven probabilistic modeling. Greco et al. (2021) and Podofillini et al. (2023) pioneered this transition by demonstrating that Bayesian models—whether hierarchical or traceable Bayesian Belief Networks—are capable of capturing crew-to-crew variability, reducing expert bias, and enabling dynamic model updates when new data become available. Y. Kim et al. (2023) reinforced this direction through data-informed dependency assessment, correcting unrealistic independence assumptions between Human Failure Events (HFEs), while Yang et al. (2024) developed a causal Bayesian network that links managerial and organizational factors to human-failure probability in process industries. These developments indicate that modern HRA is no longer merely concerned with calculating HEP but with constructing probabilistic representations that more accurately reflect operational reality.

At the same time, the integration of fuzzy logic has emerged as a response to the limitations of classical HRA in addressing linguistic uncertainty and expert subjectivity. Ciani et al. (2021) applied fuzzy HRA in the railway sector to reduce ambiguity in PSF assessments, whereas Aghaei et al. (2021) introduced Z-HEART, which incorporates Z-numbers to embed confidence weighting into expert judgments. Zhang et al. (2021), adapted fuzzy HEART for industrial maintenance activities and formulated a hesitant fuzzy linguistic version of THERP to estimate HFE dependencies in healthcare settings. Collectively, these findings show that fuzzy logic softens the rigid categorical boundaries of traditional HRA and provides more stable HEP estimations in situations where quantitative data are insufficient or inconsistent.

Another major development is the emergence of dynamic HRA, an approach that views human-error risk as a variable that evolves over time and across changing work conditions. Liinasuo et al. (2020) demonstrated that modern control rooms require HRA methods capable of adapting to situational dynamics, while Park & Boring (2025), through the EMRALD platform, showed that operator-error probabilities can shift significantly during ELAP scenarios in PWR. Jung et al. (2024) updated the time-reliability correlation model to better align with the characteristics of modern digital HMIs, correcting the shortcomings of the classical THERP-based TRC. Simulation- and data-driven approaches have also expanded rapidly, as evidenced by Wang et al., (2021) who employed Monte Carlo methods to model underground-mine operator reliability. Lu (2023), who formulated mental-overload estimation using VACP and Bayesian networks. Park et al., (2022) further demonstrated that simplified simulators such as SHEEP can substantially enrich HRA data sets without significant cost.

The trajectory of HRA methodological transformation becomes increasingly integrative as probabilistic, fuzzy, dynamic, and simulation-based approaches are merged with systems engineering and human-factors perspectives. Alencar et al. (2025) integrated FRAM and fuzzy CREAM to map functional variability in underground mining operations, while Hamza & Diaconeasa (2022) showed that applying HRA from the early design phase can eliminate unnecessary operator actions and enhance the reliability of next-generation nuclear systems. Vechgama et al. (2024) contextualized PSFs and HEP for the TRIGA research reactor, and Reza et al. (2024) demonstrated that integrating quantitative models with organizational variables strengthens the effectiveness of safety interventions. Collectively, these methodological advances reposition HRA from merely a technique for quantifying human error into an analytical framework capable of capturing behavioral complexity, predicting dynamic risk patterns, and guiding system and organizational design with far greater precision and adaptability.

Translating HRA Findings into Human-Error Prevention Strategies

The application of Human Reliability Analysis (HRA) across the 30 reviewed studies demonstrates that its outputs extend far beyond generating error-probability estimates; they directly guide organizations in formulating more precise prevention interventions. In high-risk environments such as the nuclear sector, Hamza & Diaconeasa (2022) showed that integrating HRA from the reactor-design stage can eliminate operator actions that do not contribute to safety, thereby reducing workload and improving system-control effectiveness. Jung et al. (2024), through the SAM-L2HRA method, demonstrated that identifying the most vulnerable tasks within Severe Accident Management Guidance (SAMG) allows organizations to concentrate training efforts on critical points that contribute most significantly to error. Greco et al. (2021), Podofillini et al. (2023), and Vechgama et al. (2024) further emphasized that Bayesian models and PSF adjustments based on real operational data enable organizations to prioritize technical interventions for accident scenarios with the highest error probabilities. These findings indicate that HRA is no longer merely an analytical technique but has evolved into a prevention-oriented safety-design tool.

In the process, energy and mining industries, HRA has been effectively used to redesign work procedures, enhance training standards, and improve organizational governance. Yang et al. (2024) demonstrated that causal Bayesian networks can reveal the organizational factors most influential to human reliability, enabling companies to direct interventions toward management structures, communication practices, or workload distribution in a measurable way. In underground mining, Dantas et al. (2025) found that integrating FRAM and fuzzy CREAM can identify work functions highly sensitive to disruptions, resulting in preventive recommendations focused on reorganizing workflow, improving lighting quality, and reducing operators’ mental workload. Similarly, Mohammadfam et al. (2022), using the Fuzzy Delphi and DEMATEL methods, emphasized that design errors in mining stem from organizational mismanagement, insufficient training, and poor communication systems—indicating that improvements must target organizational policies rather than merely technical worker skills.

In manufacturing, transportation, and other high-risk operational environments, HRA serves as a guide for addressing human-based errors through accurate mapping of task criticality. Hung & Dai (2024), using SHERPA, identified more than 50 error types in maritime helicopter-hoist operations, providing the foundation for developing new checklists, improving communication protocols, and redesigning work sequences to increase safety. Jiang et al. (2022) found that the most critical errors in chemical-accident emergency response occur during the initial handling stage, suggesting that training should focus on strengthening first-response capability. In the Indonesian packaging industry, Riyadi and Winarno (2023) showed that the highest HEP values arise from verification activities and SOP violations, indicating that prevention efforts must include strengthening safety discipline, increasing direct supervision, and simplifying work instructions. Neves et al. (2024) and Ciani et al. (2021) further demonstrated that in railway transportation, reducing human error is only effective when PSFs such as operator experience, environmental conditions, and supervision quality are improved in parallel.

A central theme across all articles is that strategies for preventing human error cannot succeed without organizational-level change. Bussier and Chong (2022) demonstrated that psychological distress among high-altitude workers is a critical risk indicator that must be managed through psychosocial approaches rather than through technical training alone. Zgair et al. (2023) emphasized that safety culture and TQM serve as the most effective foundations for preventing human error across sectors, while Guglielmi et al. (2022) explained that human barriers—such as cross-shift communication, non-punitive incident reporting, and procedural clarity—constitute critical layers of defense within modern organizational systems. Together, these findings illustrate that HRA is not merely a tool for mapping risk but a strategic framework for shaping organizational culture, policy, and system design to comprehensively reduce the likelihood of human error

CONCLUSION

This study concludes that Human Reliability Analysis (HRA) plays a strategic role in preventing human error across various high-risk industrial sectors. Through a systematic analysis of 30 articles, it was found that HRA functions not only as a method for quantifying error probabilities but has evolved into an analytical framework capable of mapping human factors, organizational factors, and task conditions that influence operator performance. Contemporary approaches such as Bayesian HRA, fuzzy logic, Monte Carlo simulation, FRAM–CREAM, and Dynamic HRA demonstrate that modern models are far more capable of capturing uncertainty, variability, and the dynamic nature of human behavior compared with classical deterministic methods such as THERP or HEART. These findings reinforce that probabilistic and data-driven models are essential for improving the accuracy of Human Error Probability (HEP) predictions.

This review also affirms that human error is a multidimensional phenomenon shaped by the interaction between individual, organizational, and task-related factors. Individual factors such as mental workload, situational awareness, fatigue, and psychological distress have been shown to significantly affect operator reliability. At the organizational level, the quality of training, safety leadership, safety culture, communication, and supervision emerge as strong determinants influencing the likelihood of error. At the task level, procedure complexity, time pressure, working-environment conditions, and the structure of human–machine interactions are proven to be primary triggers that elevate error risk. Collectively, these findings indicate that human error prevention can only be effective when interventions address all three dimensions simultaneously.

The results of this review show that the implementation of HRA delivers tangible impacts for organizations in developing safety programs and improving work systems. Numerous studies confirm that HRA can identify the most critical work steps, enhance procedural design, support the simplification of human–machine interfaces, and guide risk-oriented training. Across nuclear energy, mining, transportation, and SAR organizations, the application of HRA has consistently produced more targeted mitigation strategies—ranging from strengthening checklists and redesigning tasks to improving the effectiveness of training for abnormal operating conditions. These findings demonstrate that HRA functions not only as a diagnostic tool but also as a strategic instrument for shaping operational safety policy.

This study further affirms that integrating HRA into organizational management systems is a fundamental step toward building a safer, more adaptive work environment that is resilient to critical human-induced failures. Modern HRA enables organizations to understand the root causes of error comprehensively, predict failure probabilities with greater accuracy, and establish intervention priorities that directly enhance operational safety and reliability. Accordingly, this research provides strong empirical evidence that HRA must become an integral component of organizational safety strategies in today's era of complex and highly digitalized systems.

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