2026 Volume: 02 Issue: 07 www.ijrpa.com ISSN 2456-9995 Review Article

International Journal Research Publication Analysis

Page: 01-25

IMPROVING SAFETY MANAGEMENT SYSTEMS IN CHEMICAL MANUFACTURING THROUGH CRITICAL HUMAN FACTORS: AN HFACS-PROCESS SAFETY INTEGRATION FRAMEWORK

***Duan Yongbin**

Farabi International Business School, Al-Farabi Kazakh National University, Kazakhstan.

Article Received: 08 June 2026
Article Revised: 28 June 2026
Published on: 18 July 2026

***Corresponding Author: Duan Yongbin**
Farabi International Business School, Al-Farabi Kazakh National University, Kazakhstan.

DOI: https://doi-doi.org/101555/ijrpa.9041

ABSTRACT

Research Question: How can multidimensional human factors, including individual behaviour, psychological and physiological states, team supervision, human-machine interfaces and organisational governance, be embedded in the safety management systems of chemical manufacturers so that human-factor risks can be systematically identified, quantitatively assessed, specifically controlled and continuously improved?

Motivation: Chemical safety management has traditionally emphasised equipment integrity, process control and regulatory compliance. However, accident investigations repeatedly show that so-called operator error is usually only the final manifestation of a wider failure chain. Fatigue, insufficient competence, handover deficiencies, alarm design, contractor interfaces, supervisory practices and safety culture jointly shape human behaviour. As intelligent production increases the complexity of human-machine coordination and information load, management approaches based mainly on punishment, training counts or accident rates cannot adequately explain or prevent recurring events.

What's New? This paper integrates the Human Factors Analysis and Classification System (HFACS), the Swiss Cheese Model, risk-based process safety, safety-climate research, human reliability analysis and ergonomics. It develops a human-factors safety-governance framework for chemical manufacturing comprising six risk dimensions, twenty-four secondary indicators, three evidence sources and a five-stage closed loop.

So What? The framework gives enterprises a diagnostic tool for shifting from blaming an individual to repairing the system conditions that produce unsafe behaviour. It also offers a phased implementation pathway covering short-term behavioural and operational controls, medium-term organisational adjustment and long-term ergonomic upgrading. The framework can support corporate self-assessment, regulatory inspection, contractor management and digital safety-platform development.

Idea: Human factors in chemical accidents are not a single variable. They emerge through a layered transmission of organisational influences, supervisory deficiencies, preconditions for unsafe acts and unsafe acts. Effective management must address competence and fatigue, procedural usability, team communication, interfaces and alarms, resource allocation, performance incentives and learning culture, while using auditable leading and outcome indicators to test whether interventions work.

Data: The paper draws on published research in ergonomics, process safety, safety culture, automation and organisational accidents. It also conducts a structured comparison of publicly available investigation reports concerning BP Texas City, T2 Laboratories, Tesoro Anacortes, Chevron Richmond, Arkema Crosby, DuPont La Porte and Husky Superior.

Tools: The study uses an integrative literature review, accident-chain comparison, mechanism mapping and framework synthesis. HFACS identifies causal levels; risk-based process safety connects governance elements; human reliability methods and the Analytic Hierarchy Process (AHP) inform the proposed quantification approach; and a pilot-validation protocol specifies pre-post comparison, data triangulation and ethical controls for future enterprise research.

Findings: Existing systems display three principal mismatches: the absence of standardised mechanisms for identifying and monitoring human-factor risks; punishment-centred management that fails to remove root causes and may suppress reporting; and an overreliance on injury and accident outcomes that does not provide timely visibility of fatigue, competence, procedures, interfaces or organisational conditions. The paper therefore develops a six-dimensional indicator system, a graded scoring method and an identify-assess-intervene-monitor-improve loop. It also identifies poor data quality, metric gaming, excessive surveillance and responsibility transfer as major implementation risks.

Contribution: The paper extends HFACS from a post-accident classification tool into an ex ante design logic for safety management systems. It also explains how human-factors governance can improve process safety through executable procedures, competence matching, team coordination, appropriate trust and organisational learning.

KEYWORDS: Chemical manufacturing; process safety; human factors; HFACS; safety management system; safety climate; human-machine collaboration; risk assessment.

1 INTRODUCTION

Chemical manufacturers face flammable, explosive, toxic and corrosive materials, high temperatures and pressures, and continuous production. Unlike ordinary occupational injuries, process safety events are often low-frequency, high-consequence occurrences whose effects extend across organisational and geographical boundaries. A single loss of control may cause casualties, environmental contamination, asset damage and lasting social harm. Modern process safety management therefore includes process hazard analysis, mechanical integrity, operating procedures, management of change, contractor management, emergency response and organisational learning (CCPS, 2007; OSHA, 1992; OECD, 2023). Yet the existence of a formal system does not ensure that it is correctly understood, convenient to use or consistently followed in real work.

After an accident, treating the frontline operator's error as the root cause is common but limited. Reason (1990, 1997) argues that human error should be understood as the visible outcome of weaknesses in organisational defences. Rasmussen (1997) further shows that continuing pressure among efficiency, workload and safety boundaries can cause organisations to drift. Systems theory likewise locates accidents in failed safety constraints and control rather than in a single component or individual (Leveson, 2011). Operational errors, violations, omissions and misjudgements must be managed, but the more important question is which task conditions, information environments, supervisory practices and organisational decisions make such behaviour more likely.

Intelligent upgrading has not eliminated human-factor risk; it has changed its form. Automated control can reduce repetitive workload but may also produce skill degradation, mode confusion, automation dependence and information overload during abnormal conditions. Bainbridge's (1983) ironies of automation remain relevant to modern control rooms: the more routine activity is automated, the less operators participate in normal operations, yet the more demanding their cognitive work becomes when the system fails. Operators must form situation awareness from large volumes of alarms, trends and interlock states, and decide when to trust, question or take over from automation (Endsley, 1995; Parasuraman & Riley, 1997; Lee & See, 2004). Human-machine interface design, alarm management, competence retention and team coordination should therefore be core elements of a safety management system.

Existing scholarship offers several complementary traditions. HFACS links unsafe acts, preconditions for unsafe acts, unsafe supervision and organisational influences in a hierarchical structure (Shappell & Wiegmann, 2000). Safety-climate research explains how management commitment, supervisory practice and shared employee perceptions affect safety motivation and behaviour (Zohar, 1980; Neal & Griffin, 2006). Human reliability analysis provides tools for task decomposition and error-probability assessment (Kirwan, 1994; Bell & Holroyd, 2009), while risk-based process safety provides enterprise-level governance elements (CCPS, 2007). The problem is that these methods are often applied separately: investigators code events using HFACS, safety departments administer surveys, engineering teams conduct HAZOP or LOPA, and human-resource departments organise training, without necessarily connecting these activities in a common risk-control loop.

This paper asks: how can chemical manufacturers construct a safety management system that uses causal human factors as its organising logic while connecting people, tasks, technology, teams and the organisation? The paper does not fabricate survey, interview or pilot data. Instead, it uses an integrative review and public accident reports to complete three tasks: diagnose structural mismatches between existing systems and human-risk control needs; propose a multidimensional risk-assessment system and its evidence sources; and design a phased optimisation programme that can be implemented and tested in enterprises. The central contribution is to convert post-accident human-factor explanation into pre-accident management-system design.

2 LITERATURE REVIEW AND ANALYTICAL FRAMEWORK

2.1 From individual blame to systemic human-factors governance

Traditional safety management readily attributes accidents to inattention, procedural violations or inadequate training, and responds with additional punishment and retraining. This approach can address deliberate misconduct, but it cannot explain why similar errors recur across shifts, units and time periods. A systemic perspective distinguishes active failures from latent conditions: active failures occur close to the event, whereas latent conditions are embedded in design, resources, objectives, communication and managerial decisions (Reason, 1997). Where procedures conflict with real tasks, staffing remains inadequate, alarms continually flood operators, or production indicators override safety goals, asking operators to be more careful can only mask the problem temporarily.

Dekker (2014) argues that decisions should be understood from the information and constraints available when the behaviour occurred, rather than by using the outcome to infer what the person should have known. Just culture further distinguishes inadvertent error, at-risk behaviour and reckless behaviour, enabling organisations to preserve accountability without suppressing reporting and learning (Dekker, 2016). Safety-II shifts attention from failure alone to how everyday work succeeds despite limited resources and changing conditions, thereby recognising human adaptability (Hollnagel, 2014). Together, these perspectives show that human-factors governance does not remove individual responsibility; it places responsibility within executable systems, reasonable task demands and organisational learning.

2.2 HFACS, human reliability and accident chains

HFACS was developed for aviation accident analysis, and its structure supports upward tracing from surface errors. The first level, unsafe acts, includes decision errors, skill-based errors, perceptual errors and violations. The second level, preconditions for unsafe acts, covers environmental conditions, personnel states and team resources. The third level, unsafe supervision, includes inadequate supervision, inappropriate planned operations, failure to correct known problems and supervisory violations. The fourth level, organisational influences, includes resource management, organisational climate and organisational processes (Shappell & Wiegmann, 2000). In chemical operations, this structure can connect an incorrectly opened valve, a missed inspection, an incorrect isolation or a procedural deviation with fatigue, shift handover, competence, permits to work, contractor interfaces and management priorities.

Human reliability analysis examines how errors arise in specific tasks and how their likelihood can be estimated, commonly using task analysis, performance-shaping factors and expert judgement (Kirwan, 1994; Bell & Holroyd, 2009). HFACS and human reliability methods are complementary: HFACS supports organisational-level classification, while reliability methods support scenario-specific and task-step quantification. HSE human-factors guidance similarly emphasises that competence, procedures, workload, fatigue, communication, organisational change and human-machine interfaces should be included in major-hazard management rather than reducing human factors to operator reliability (HSE, 1999, 2005).

2.3 Safety climate, supervision and organisational learning

Safety climate reflects employees' shared perceptions of an organisation's real priorities. Zohar's (1980) foundational study showed that management emphasis on safety, supervisory consistency and the enforcement of procedures create a perceptible climate. Subsequent reviews distinguish the deeper values of safety culture from the measurable perceptions of safety climate, and repeatedly identify management commitment, communication, participation and learning as central dimensions (Flin et al., 2000; Guldenmund, 2000; Wiegmann et al., 2004). Parker, Lawrie and Hudson (2006) further describe cultural development as a progression from reactive and calculative to proactive and generative forms.

Empirical evidence generally supports relationships among safety climate, behaviour and accidents. Meta-analyses by Clarke (2006), Christian et al. (2009) and Nahrgang et al. (2011) show that safety knowledge, motivation, participation, job demands and resources jointly influence safety performance. Neal and Griffin (2006) find that safety climate has lagged effects through safety motivation and behaviour. At the same time, punitive accountability and weak psychological safety may suppress the reporting of accidents and near misses, improving superficial indicators while allowing actual risk to rise (Probst & Estrada, 2010). Organisations therefore need clear rules while ensuring that employees can challenge decisions, report weak signals and participate in improvement.

2.4 Human-machine interfaces, fatigue and team coordination

Chemical control rooms and field operations depend heavily on human-machine interaction. Situation awareness comprises the perception of environmental elements, comprehension of their meaning and projection of future states (Endsley, 1995). When interface presentation conflicts with operators' process understanding, alarm volumes are excessive or mode changes lack feedback, operators may form incorrect mental models at critical moments. Automation should support appropriate reliance rather than blind trust or complete rejection (Parasuraman & Riley, 1997; Lee & See, 2004). Human-factors methods can identify these risks through task analysis, cognitive work analysis, usability assessment and control-room observation (Stanton et al., 2013).

Fatigue, stress and workload impair attention, memory, judgement and communication. Research on offshore drilling crews has found significant relationships among stress, fatigue, situation awareness and safe behaviour (Sneddon et al., 2013). A meta-analysis of team training also shows that programmes focused on communication, shared mental models and coordinated decision-making can improve team performance (Salas et al., 2008). Chemical safety training should therefore assess not only whether individuals have attended a course, but whether teams can coordinate during abnormal conditions, shift handovers, joint isolations and emergency response.

2.5 An integrated HFACS-process safety model and research propositions

Risk-based process safety organises enterprise activity around commitment, hazard understanding, risk management and learning from experience. It emphasises the systemic links among competence, workforce involvement, operating procedures, safe-work practices, management of change, contractor management, incident investigation and performance measurement (CCPS, 2007). The CCPS human factors handbook further embeds human factors in design, operation, maintenance and organisational management (CCPS, 2022). API RP 754 uses tiered indicators to distinguish major process safety events, lower-consequence events and leading management activities (API, 2021). ISO 45001 and ISO 45003 provide frameworks for occupational health and safety management and psychosocial-risk governance, respectively (ISO, 2018, 2021).

Four propositions follow. Proposition 1: human-factors interventions reduce recurring events more effectively than punishment alone when enterprises trace unsafe acts to task, supervisory and organisational conditions, and assign corrective responsibility to the management level able to change those conditions. Proposition 2: human-factor risk becomes more visible and auditable when assessment combines questionnaires, field observation and operational data, and integrates leading and outcome indicators. Proposition 3: organisational learning improves when reporting systems apply just-culture principles, protect the reporting of ordinary errors and retain accountability boundaries for reckless behaviour. Proposition 4: automation reduces rather than transfers human-factor risk when digital tools are implemented together with ergonomics, competence management and workforce participation.

Table 1: Complementarity of theoretical foundations, analytical objects and contributions to human-factors governance in chemical manufacturing.

Theory or tool	Core analytical object	Contribution to chemical safety management	Limitation when used alone
Swiss Cheese Model and	Defence-layer weaknesses, latent	Prevents direct operator error from being treated	Provides limited guidance on specific

Theory or tool	Core analytical object	Contribution to chemical safety management	Limitation when used alone
systems accident theory	conditions and organisational control	as the root cause	indicators and weights
HFACS	Unsafe acts, preconditions, supervision and organisational influences	Provides a common classification and causal-tracing pathway	Requires adaptation to chemical tasks and process contexts
Human reliability analysis	Task steps, error modes and performance-shaping factors	Supports semi-quantitative or quantitative assessment of critical work	Sensitive to expert judgement and weak in representing organisational culture
Safety climate and just culture	Management commitment, supervisory consistency, participation and reporting	Reveals gaps between formal systems and actual priorities	Surveys may be influenced by social desirability and temporary sentiment
Ergonomics and automation research	Interfaces, alarms, workload, trust and situation awareness	Improves the design of control rooms, field equipment and digital systems	Technical optimisation cannot replace resource and governance reform
Risk-based process safety	Governance elements, hazard control and continuous improvement	Embeds human factors in procedures, training, change and performance management	May remain compliance-checklist driven when human-factor indicators are absent

3 METHOD

3.1 Research design, object and boundaries

This paper uses an integrative review and framework-building design. Its object is medium-sized and large high-hazard manufacturing enterprises in petrochemicals, fine chemicals and hazardous-chemical production. The analytical settings include production units, central control rooms, maintenance and non-routine work, warehousing and loading, contractor activities and safety departments. The focus is not individual differences among employees but the interaction between multidimensional human factors and the everyday operation of safety management systems, including error formation, organisational culture, supervisory practice, human-machine fit and the effects of improvement measures on system performance.

The research boundary distinguishes occupational safety from process safety without treating them as entirely separate. Personal-injury indicators such as slips and cuts cannot substitute for major-accident risk indicators. Equally, fatigue, psychological pressure and team communication affect both occupational health and the response to process abnormalities. This paper centres on major-hazard control while incorporating psychosocial risks that directly affect task reliability.

3.2 Evidence sources and accident cases

The theoretical evidence comprises foundational studies, meta-analyses, books and standards in ergonomics, organisational accidents, safety culture, automation, team performance and process safety management. Accident evidence was selected from well-documented public investigations capable of revealing organisational and human-factor chains. Cases include the BP Texas City refinery explosion, the T2 Laboratories runaway reaction, the catastrophic heat-exchanger rupture at Tesoro Anacortes, the Chevron Richmond pipe rupture, the Arkema Crosby organic-peroxide fires, the DuPont La Porte toxic release and the Husky Superior refinery explosion (CSB, 2007, 2009, 2014, 2015, 2018, 2019, 2022).

These cases are not used to estimate accident proportions across the chemical industry. They are used to identify mechanisms that recur across contexts. Texas City demonstrates the combined influence of start-up procedures, competence, fatigue, facility siting, alarms and organisational culture; Hopkins (2008) uses the case to explain how an organisation can possess extensive systems yet still fail to learn. The other cases illustrate inadequate understanding of reaction hazards, equipment degradation, management of change, isolation and work permits, severe-weather preparedness, contractor interfaces and human factors in emergency decision-making.

Table 2: Evidence system, analytical purpose and quality controls.

Evidence category	**Representative material**	**Primary analytical purpose**	**Quality control**
Foundational theory	Reason, Rasmussen, Leveson, Hollnagel and related work	Defines systems accidents, organisational drift and resilience	Compares assumptions and applicability across theories
Human-factor classification and reliability	HFACS, HRA and HSE human-factors guidance	Builds causal levels and task-risk dimensions	Avoids mechanically copying aviation classifications into chemical operations

Evidence category	Representative material	Primary analytical purpose	Quality control
Safety culture and behavioural research	Safety-climate meta-analyses, longitudinal studies and just-culture research	Links management commitment, reporting and behavioural outcomes	Prioritises multi-sample, meta-analytic and longitudinal evidence
Process safety standards	CCPS RBPS, API RP 754 and ISO 45001/45003	Embeds human-factor indicators in management elements and performance measurement	Distinguishes formal requirements from the paper's proposed extensions
Official accident investigations	Public CSB investigation reports and recommendations	Supports accident-chain comparison and counterfactual testing	Retains case-specific context and avoids inferring industry-wide proportions from single cases

3.3 Analytical procedure

The analysis proceeded in four steps. First, causal descriptions in the literature and accident reports were classified by HFACS level, with additional tags for human-machine interfaces, contractors and non-routine work that are especially important in chemical operations. Second, each human factor was mapped to process safety management elements to determine whether corrective responsibility should rest with operators, team supervisors, engineering, human resources, the safety function or senior governance. Third, recurring combinations were compared across cases to identify why isolated measures fail, such as training without procedural revision, digital monitoring without challenge and feedback mechanisms, or punishment without resource adjustment. Fourth, the findings were synthesised into risk indicators, scoring logic, an intervention matrix and a pilot-validation design.

To prevent human factors from becoming an overly broad and non-operational label, three decision criteria were applied. An indicator must correspond to a changeable management condition; its data must be verifiable through at least one independent source; and the assessment result must trigger a defined accountable owner and a correction deadline. Cultural and leadership factors that are difficult to quantify directly should be triangulated through surveys, interviews, observations and system records rather than treating a single attitude survey as an objective risk value.

3.4 Indicator construction and protocol for subsequent empirical validation

The proposed indicator system contains six first-order dimensions, with weights to be determined through AHP or another multi-criteria method. In enterprise application, representatives from process engineering, safety, human factors, operations, maintenance and the frontline workforce should jointly conduct pairwise comparisons and consistency tests. Scores should not rely on a single data source. A Human-Factor Risk Index may be expressed as $HFRI = \Sigma\, w_j(\alpha Q_j + \beta O_j + \gamma D_j)$, where w_j is the indicator weight; Q_j is the standardised questionnaire or interview score; O_j is the observation and audit score; D_j is the operational-data score; and α, β and γ reflect the reliability of the respective evidence sources. The formula is intended to organise priorities, not to claim precise prediction of an individual accident.

Future enterprise pilots should use a pre-post comparison lasting at least six months and retain a defined baseline period. Core outcomes include the violation rate in major-hazard work, the quality of near-miss reporting, procedural deviations, alarm load, excessive working hours, competence-matrix gaps, the quality of corrective-action closure and employee risk perception. Because accident counts are usually small and subject to random variation, effectiveness should not be judged only by whether accidents decline. Leading indicators and process behaviour must also be examined.

3.5 Ethics and data governance

This paper uses public information and involves no human participants; ethical review is therefore not applicable. Future enterprise surveys, interviews and field observations should obtain voluntary informed consent, replace names with role codes, restrict access to raw data and specify that data must not be used for punitive individual rankings. Enterprise and personal information should be anonymised, while trade secrets, process parameters and accident-liability data should be used only within authorised limits. Digital monitoring must follow the principles of necessity, proportionality and purpose limitation so that safety tools do not become excessive surveillance.

4 ANALYTICAL FINDINGS AND SYSTEM DESIGN

4.1 Three core mismatches in existing safety management systems

The first mismatch is an inadequate identification mechanism. Most enterprises can record violations, accidents and training, but they lack a common structure for analysing fatigue, competence, procedural usability, alarms, communication, supervision and organisational objectives. The same event may consequently be classified by different departments as an operational, equipment or management problem, producing fragmented corrective actions. HFACS can provide a common language, but its levels must be mapped to units, tasks and management-system elements.

The second mismatch is a control approach centred on end-point behaviour. Punishment can communicate non-negotiable boundaries, but it may conflate ordinary error, adaptive at-risk behaviour and reckless conduct. When employees believe that reporting will lead directly to punishment, near misses, unusable procedures and weak equipment signals are more likely to be hidden. The organisation gains the silence of no reports, not lower risk. An effective system should preserve accountability boundaries within a just culture while directing most corrective resources towards the system conditions that shape behaviour.

The third mismatch is an overemphasis on lagging indicators. Injury rates and accident counts describe outcomes, but for low-frequency major accidents they are statistically unstable and may be affected by production volume, reporting practices and chance. Activity indicators such as training completion and inspection counts can also become formalities. Human-factor evaluation needs to connect four levels: whether conditions are safe, behaviour is reliable, defences are effective and outcomes are improving.

4.2 Unsafe acts: from error categories to task contexts

Unsafe acts in chemical operations can be grouped into skill-based errors, decision errors, perceptual errors and violations. Skill-based errors include omissions, sequence confusion and action mismatches in repetitive work. Decision errors occur when information is incomplete or rules do not fit the situation. Perceptual errors are associated with labels, lighting, displays and alarms. Violations require distinctions among habitual deviation, situational adaptation and reckless behaviour undertaken with knowledge of high risk. The same observable act can have different root causes, so corrective action should not automatically be equated with retraining.

Accident reports show that low-frequency, high-risk tasks such as start-up and shutdown, abnormal operations, maintenance isolation, hot work and confined-space entry most readily expose gaps between procedures and work as done. When procedures are excessively long, information is dispersed, versions are obsolete or abnormal states are omitted, workers develop local work methods. If those methods repeatedly succeed during normal operations, deviation may become normalised until changing conditions cause the defences to fail.

4.3 Preconditions for unsafe acts: fatigue, competence, teams and human-machine fit

Preconditions for unsafe acts are the HFACS level most suitable for proactive monitoring. Individual states include fatigue, stress, attention, health and risk perception. Competence conditions include knowledge, skills, experience and training for abnormal situations. Team conditions include shift handover, shared task understanding, closed-loop communication and cross-functional coordination. Environmental conditions include lighting, noise, temperature, personal protective equipment and workspace. Human-machine conditions include control logic, alarm prioritisation, labelling consistency, equipment accessibility and automation transparency.

These factors have configurational effects. An inexperienced employee may complete a task safely under clear procedures and adequate supervision, while an experienced employee may err under fatigue, alarm flooding and time pressure. Risk assessment should therefore avoid treating stable personality characteristics as the main explanation and instead evaluate the fit among the person, task, time and system.

4.4 Supervision, organisation and cross-boundary interfaces

At the supervisory level, assessment should determine whether plans are realistic, personnel are competent, permits and isolations receive independent verification, known problems are corrected, pre-job meetings address actual hazards, and field managers tolerate deviations under production pressure. Supervision is not simply an increase in inspection frequency; it ensures that task resources, boundaries and escalation routes for abnormal conditions are clear before work begins.

At the organisational level, relevant factors include safety culture, resource allocation, objectives and incentives, management of change, contractor governance, procurement and design, and learning mechanisms. Major accidents frequently occur at departmental and organisational boundaries: operations and maintenance understand equipment status differently; owners and contractors use inconsistent labels; senior cost decisions weaken staffing or maintenance resources; and engineering changes are not accompanied by updated procedures and training. Unless these interfaces are governed, organisations transfer system risk to the people nearest the hazard.

4.5 A multidimensional critical human-factor risk indicator system

Drawing on theory and accident evidence, this paper proposes six first-order dimensions and twenty-four second-order indicators. Indicators were selected for actionability, observability and traceability. Enterprises may add or remove indicators according to unit hazards and data maturity, but they should not delete organisational or human-machine levels and retain only behavioural inspection.

Table 3: Critical human-factor risk assessment indicators for chemical manufacturing.

First-order dimension	Examples of second-order indicators	Primary data sources	High-risk signals
Individual behavioural reliability	Procedural compliance; omission of critical steps; abnormal-condition decisions; at-risk or reckless violations	Behavioural observation, permit records and incident investigation	Repeated similar deviations; critical steps depend on memory; no decision support for abnormal states
Psychophysiological state and competence	Fatigue and working hours; stress and attention; role competence; abnormal-condition training	Roster data, competence matrices, questionnaires and drills	Consecutive excessive hours; inadequate backup for critical roles; training assesses theory only
Team and supervisory control	Handover quality; closed-loop communication; task planning; supervisory correction	Handover records, field observation, audits and interviews	Inconsistent status information; known issues remain open; supervisors tolerate deviation
Human-machine and task fit	Alarm load; interface comprehensibility; labelling consistency; tools and workspace	Alarm logs, usability tests and task analysis	Alarm flooding; opaque modes; similar valves or lines are difficult to distinguish
Organisational safety climate	Management commitment; workforce participation; reporting fairness; balance of production and safety goals	Safety-climate surveys, interviews and meeting records	Employees fear reporting; safety concerns receive no resources; performance systems reward output only
System and cross-boundary governance	Management of change; contractor interfaces; procedure lifecycle; learning and performance measurement	MOC records, contracts, procedure versions, investigations and audits	Changes do not update training; contractor standards are inconsistent; corrective actions target individuals only

4.6 Quantitative assessment: weights, evidence and risk grading

The purpose of indicator quantification is not to create an apparently precise human accident probability, but to compare risks, track trends and prioritise improvement. Assessment units should first be defined by plant area or task, after which AHP can determine first- and second-order weights. High-consequence, low-frequency tasks may assign greater weight to competence, human-machine interfaces and supervisory verification. Continuous-control tasks may emphasise alarms, workload and situation awareness, while contractor-intensive maintenance should emphasise interfaces and permit management.

Scoring should use evidence triangulation. Fatigue risk, for example, should not be based only on whether workers report feeling tired; it should also consider consecutive working days, night shifts, overtime and short-notice replacement. Procedural usability should not be assessed solely by checking that a document exists; evaluators should observe whether workers can locate and correctly use it at the worksite. Safety climate should not rely only on a mean survey score; near-miss reporting, issue escalation and corrective resources should also be compared. Where survey and operational data conflict substantially, the conflict itself should be treated as a management signal.

Risk may be graded as acceptable, requiring attention, significant or unacceptable, with defined actions attached to each level. Unacceptable risk should trigger task suspension or redesign. Significant risk requires time-bound engineering or organisational correction. Risks requiring attention enter trend monitoring, while acceptable risks still require control maintenance. Jobs and teams must be able to explain or challenge scoring results so that algorithms or expert weights do not become unquestionable authority.

4.7 Phased optimisation of the safety management system

The short-term objective is to interrupt the most immediate failure chains. Enterprises should revise high-risk work procedures, establish independent verification of critical steps, improve shift handover and equipment-status identification, control excessive hours, remove nuisance alarms, and clarify abnormal-condition escalation and stop-work authority. Short-term measures should prioritise start-up and shutdown, energy isolation, line opening, hot work, confined-space entry and runaway-reaction scenarios.

The medium-term objective is to change organisational mechanisms. Enterprises should establish competence matrices and dynamic authorisation, implement a just culture differentiated by behaviour type, integrate contractor training and permit systems, include human-factors review in management of change and incident investigation, and replace punishment-only responses with team coaching. The safety function should expand from inspection to rule design, data analysis and cross-functional coordination.

The long-term objective is to redesign human-machine systems at source. Enterprises should reduce task demands through ergonomic modification of control rooms and field equipment, an alarm-management philosophy, maintainability design, digital twins or simulation training, intelligent scheduling and risk-warning systems. Long-term digitalisation must preserve human understanding, abnormal-condition takeover and feedback channels so that over-automation does not produce skill loss or invisible risk.

Table 4: Short-, medium- and long-term pathways for human-factors optimisation.

Phase	Principal measures	Accountable functions	Expected outcome	Implementation risk
Short term: behavioural and operational control	Rewrite critical procedures; independent verification; handover standards; fatigue limits; alarm clean-up; stop-work authority	Operations, maintenance, safety and frontline teams	Rapid reduction in omissions and state misidentification during high-risk work	Temporary inspection replaces root-cause correction; excessive measures create procedural burden
Medium term: organisational adjustment	Competence matrices; just culture; contractor integration; human-factors review in MOC; team coaching; reporting protection	Middle and senior management, HR, safety, procurement and contractor management	Improved reporting, learning, supervisory consistency and resource matching	Unclear accountability; just culture is misinterpreted as no accountability
Long term: ergonomic upgrading	Control-room and field design; alarm philosophy; simulation training; intelligent scheduling; risk-data platform	Engineering, digitalisation, operations and senior investment decision-makers	Lower cognitive load by design and stronger resilience in abnormal conditions	Technology dependence, privacy intrusion, data bias and skill degradation

4.8 Enterprise pilots and effectiveness validation

Pilots should be conducted in a unit or enterprise with clear risk boundaries, management support and basic data availability. A baseline should be measured for one to three months before implementation, followed by an intervention lasting at least six months. Evaluation should combine comparative analysis with process tracing: indicators are compared before and after implementation, while evidence is also collected on how measures are accepted, modified or resisted. Outcome changes without evidence of the implementation process cannot establish that the programme caused the improvement.

Pilot indicators should be divided into five categories: input, process, behaviour, defence and outcome. Inputs represent resources and competence; processes represent system implementation; behaviour represents the reliability of critical tasks; defences represent the quality of controls such as alarms, interlocks and permits; and outcomes represent near misses, releases and accidents. Because encouraging reporting may initially increase the number of reported near misses, reporting quality and risk-closure rates should be assessed together so that increased reporting is not misinterpreted as deteriorating safety.

Table 5: Multilevel indicators for validating pilot effectiveness.

Indicator level	Example indicators	Expected direction	Interpretive caution
Input indicators	Competence coverage in critical roles; fatigue-risk shifts; resources for human-factors correction	Competence coverage rises and fatigue-risk shifts fall	Resource input does not prove effective implementation
Process indicators	On-site procedural usability; handover closure; human-factors review rate in MOC	Sustained increase	Sample actual use rather than checking documents only
Behavioural indicators	Critical-step omission rate; isolation and permit deviations; performance in abnormal-condition drills	Sustained reduction or improvement	Control for observer effects and task difficulty
Defence indicators	Duration of alarm floods; management of interlock bypasses; overdue corrective actions	Sustained reduction	Distinguish authorised bypasses from uncontrolled bypassing
Outcome and learning indicators	High-quality near-miss reports; recurring-event rate; process safety event tier	Reporting quality rises first; recurrence and event severity fall later	Do not use one month's accident count as the sole conclusion

4.9 Integrated closed loop and boundary conditions

The proposed system forms a five-stage identify-assess-intervene-monitor-improve loop. Identification uses HFACS and task analysis to locate risk. Assessment combines weights with multiple evidence sources. Intervention applies the hierarchy of controls, prioritising elimination, engineering and organisational measures. Monitoring tracks leading and outcome indicators. Improvement feeds events, near misses and evidence of normal successful work back into procedures, design, training and resource allocation. Omitting any stage weakens the loop: identification without intervention creates reporting fatigue; quantification without appeal produces metric domination; and technical modification without competence renewal creates new forms of error.

The framework depends on at least six boundary conditions: management must be willing to allocate resources to systemic correction; data must represent real work rather than compliance documents alone; employees need psychological safety to report hazards and stop work; task and accountability boundaries must be sufficiently clear; engineering, operations, human resources and safety functions must collaborate; and digital systems must provide privacy, explainability and correction mechanisms. Without these conditions, a human-factors programme may transfer corporate responsibility to individuals or reduce complex safety problems to ranking scores.

5 DISCUSSION

5.1 Theoretical contributions

First, this paper extends HFACS from a post-accident classification framework into a design architecture for safety management systems. Whereas conventional applications code causes after an accident, this study links the four causal levels to routine indicators, accountable owners and interventions, enabling organisations to identify fatigue, procedural, supervisory and cultural conditions before an accident occurs.

Second, the paper connects micro-level human reliability with macro-level process safety governance. Task analysis explains why a particular step is error-prone; safety climate explains why employees choose to report or remain silent; and RBPS specifies how organisations allocate resources and close the management loop. Together, these perspectives show that human factors are not an additional safety module but a cross-cutting logic through which procedures, training, design, change and performance management interact.

Third, the paper qualifies the quantification of human factors. Human-factor risk can be structured and compared, but it cannot be reduced to a decontextualised individual score. Credible assessment requires multiple evidence sources, transparent weights, trend interpretation and appeal mechanisms. This position complements assessment traditions centred on technical precision and prevents digital platforms from converting complex organisational problems into individual surveillance.

Fourth, the paper connects just culture with process safety accountability. Non-punitive reporting does not eliminate accountability; it differentiates error type, behavioural intent and system conditions. Organisations should prioritise system improvement for inadvertent error, provide coaching and redesign for at-risk behaviour, retain disciplinary accountability for reckless behaviour, and hold managers accountable for known system deficiencies.

5.2 Managerial implications

Enterprises should not begin by purchasing software or administering a one-off survey. They should first identify the most consequential risk bottleneck. If high-risk procedures are not executable, procedures and equipment-state identification should be improved first. If reporting is extremely low, accountability and feedback mechanisms should be repaired. If control rooms experience alarm flooding, alarm rationalisation should take priority. If contractor incidents dominate, competence, permit and supervision standards should be aligned. Tool selection must follow diagnosis.

Implementation should use small pilots and phased expansion. An enterprise should first select one unit or task type, establish a baseline, co-design indicators and verify data quality before expanding to other areas. Management should periodically review systemic corrective actions rather than only employee violation counts. Human resources should participate in competence, scheduling and incentive design; engineering should address interfaces, maintainability and change; and procurement and contracting functions should include human-factors requirements in contractor selection and performance evaluation.

Digital platforms should support judgement rather than act as automated punishment systems. Platforms can integrate scheduling, alarm, permit, training and incident data to identify risk combinations, but high-risk determinations must permit human review. Employees should understand how their data are used and be able to correct inaccurate records. Appropriate transparency and participation are prerequisites for technological legitimacy.

5.3 Regulatory and industry implications

Regulatory inspection can move from asking whether a system exists to asking whether it works in real tasks. Inspectors can sample field activities when assessing procedural usability, evaluate abnormal-condition and team coordination capabilities when reviewing training, determine whether incident corrective actions stop at the individual level, and require major-hazard leading indicators alongside performance outcomes. The tiered-indicator logic of API RP 754 can be combined with the human-factor indicators proposed here to create an assessment focused on major-accident risk.

At industry level, anonymised human-factors databases for accidents and near misses could use a common chemical-industry extension of HFACS to support inter-firm learning. Regulators and industry associations could also issue task-specific reference indicators, fatigue and alarm benchmarks, contractor-interface checklists and human-factors review guidance, reducing duplicated development costs across enterprises.

5.4 Limitations and future research

This is a conceptual review and does not use original enterprise questionnaires, interviews, behavioural observations or operational databases. It therefore cannot estimate the empirical weights of the indicators or demonstrate that the framework will reduce accidents in every enterprise. Public accident reports document severe events and failed conditions more extensively than routine success, informal adaptation or ordinary employee experience. National differences in regulation, employment relations and reporting culture will also affect implementation.

Future research should proceed through multiple empirical stages. First, Delphi and AHP studies should assess indicator content validity and weights. Second, enterprises of different sizes and process types should be used to test reliability, construct validity and cross-group measurement equivalence. Third, longitudinal links among questionnaires, alarms, working hours, permits and near-miss data should test the predictive validity of human-factor indicators for process safety events. Fourth, punishment-oriented and just-culture interventions should be compared in terms of reporting quality, psychological safety and recurring events. Fifth, research should examine bias, explainability and ethical boundaries in artificial-intelligence-assisted risk identification.

6 CONCLUSION

Chemical manufacturing safety cannot depend only on stronger equipment, nor can accident prevention be reduced to asking employees not to make mistakes. Human behaviour is produced within a system of tasks, technology, teams, supervision and organisational objectives. Human error becomes managerially useful only when it is traced to causal conditions that can be changed.

Drawing on HFACS, systems accident theory, human reliability, safety climate, ergonomics and risk-based process safety, this paper proposes six human-factor risk dimensions and a five-stage closed loop. The framework requires enterprises to examine individual behavioural reliability, psychophysiological state and competence, team supervision, human-machine and task fit, organisational safety climate, and system and cross-boundary governance. It triangulates questionnaires, field observations and operational data, and implements improvement through short-term operational controls, medium-term organisational adjustment and long-term engineering upgrades.

The most important managerial implication is that a safety system should not search for the person most likely to make a mistake, but identify the conditions most likely to produce error, while retaining proportionate accountability for reckless conduct and managerial neglect. Human-factors management can move from post-accident explanation to pre-accident prevention only when employees can report problems, management is willing to repair systems, digital tools are governed, and leading and outcome indicators are used together.

DECLARATIONS

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

Data Availability: The public literature, standards and accident investigation reports used in this review are listed in the references. No new individual-level data were generated.

Ethics Statement: Not applicable. This study uses only publicly available published materials and involves no human participants or identifiable personal information.

Author Contributions: The author independently completed the conceptual design, literature synthesis, framework development and manuscript preparation.

Generative AI Statement: At submission, the use of AI-assisted tools should be disclosed accurately in accordance with the target journal's policy. The author remains responsible for all content, citations and conclusions.

REFERENCES

1. American Petroleum Institute. (2021). API Recommended Practice 754: Process safety performance indicators for the refining and petrochemical industries (3rd ed.). API.
2. Bainbridge, L. (1983). Ironies of automation. Automatica, 19(6), 775-779. https://doi.org/10.1016/0005-1098(83)90046-8
3. Bell, J., & Holroyd, J. (2009). Review of human reliability assessment methods (Research Report RR679). Health and Safety Executive.
4. Center for Chemical Process Safety. (2007). Guidelines for risk based process safety. John Wiley & Sons.
5. Center for Chemical Process Safety. (2022). Human factors handbook for process plant operations. John Wiley & Sons.
6. Christian, M. S., Bradley, J. C., Wallace, J. C., & Burke, M. J. (2009). Workplace safety: A meta-analysis of the roles of person and situation factors. Journal of Applied Psychology, 94(5), 1103-1127. https://doi.org/10.1037/a0016172
7. Clarke, S. (2006). The relationship between safety climate and safety performance: A meta-analytic review. Journal of Occupational Health Psychology, 11(4), 315-327. https://doi.org/10.1037/1076-8998.11.4.315
8. Dekker, S. (2014). The field guide to understanding 'human error' (3rd ed.). Ashgate.
9. Dekker, S. (2016). Just culture: Restoring trust and accountability in your organization (3rd ed.). CRC Press.
10. Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. Human Factors, 37(1), 32-64. https://doi.org/10.1518/001872095779049543
11. Flin, R., Mearns, K., O'Connor, P., & Bryden, R. (2000). Measuring safety climate: Identifying the common features. Safety Science, 34(1-3), 177-192. https://doi.org/10.1016/S0925-7535(00)00012-6
12. Guldenmund, F. W. (2000). The nature of safety culture: A review of theory and research. Safety Science, 34(1-3), 215-257. https://doi.org/10.1016/S0925-7535(00)00014-X
13. Health and Safety Executive. (1999). Reducing error and influencing behaviour (HSG48). HSE Books.
14. Health and Safety Executive. (2005). Human factors in the management of major accident hazards: Inspectors' toolkit. HSE.

15. Hollnagel, E. (2014). Safety-I and Safety-II: The past and future of safety management. Ashgate.
16. Hopkins, A. (2008). Failure to learn: The BP Texas City refinery disaster. CCH Australia.
17. International Organization for Standardization. (2018). ISO 45001:2018 Occupational health and safety management systems - Requirements with guidance for use. ISO.
18. International Organization for Standardization. (2021). ISO 45003:2021 Occupational health and safety management - Psychological health and safety at work - Guidelines. ISO.
19. Kirwan, B. (1994). A guide to practical human reliability assessment. Taylor & Francis.
20. Lee, J. D., & See, K. A. (2004). Trust in automation: Designing for appropriate reliance. Human Factors, 46(1), 50-80. https://doi.org/10.1518/hfes.46.1.50_30392
21. Leveson, N. G. (2011). Engineering a safer world: Systems thinking applied to safety. MIT Press.
22. Nahrgang, J. D., Morgeson, F. P., & Hofmann, D. A. (2011). Safety at work: A meta-analytic investigation of the link between job demands, job resources, burnout, engagement, and safety outcomes. Journal of Applied Psychology, 96(1), 71-94. https://doi.org/10.1037/a0021484
23. Neal, A., & Griffin, M. A. (2006). A study of the lagged relationships among safety climate, safety motivation, safety behavior, and accidents at the individual and group levels. Journal of Applied Psychology, 91(4), 946-953. https://doi.org/10.1037/0021-9010.91.4.946
24. Organisation for Economic Co-operation and Development. (2023). OECD guiding principles for chemical accident prevention, preparedness and response (3rd ed.). OECD Publishing.
25. Occupational Safety and Health Administration. (1992). Process safety management of highly hazardous chemicals, 29 C.F.R. § 1910.119. U.S. Department of Labor.
26. Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. Human Factors, 39(2), 230-253. https://doi.org/10.1518/001872097778543886
27. Parker, D., Lawrie, M., & Hudson, P. (2006). A framework for understanding the development of organisational safety culture. Safety Science, 44(6), 551-562. https://doi.org/10.1016/j.ssci.2005.10.003

28. Probst, T. M., & Estrada, A. X. (2010). Accident under-reporting among employees: Testing the moderating influence of psychological safety climate and supervisor enforcement of safety practices. Accident Analysis & Prevention, 42(5), 1438-1444.
29. Rasmussen, J. (1997). Risk management in a dynamic society: A modelling problem. Safety Science, 27(2-3), 183-213. https://doi.org/10.1016/S0925-7535(97)00052-0
30. Reason, J. (1990). Human error. Cambridge University Press.
31. Reason, J. (1997). Managing the risks of organizational accidents. Ashgate.
32. Salas, E., DiazGranados, D., Klein, C., Burke, C. S., Stagl, K. C., Goodwin, G. F., & Halpin, S. M. (2008). Does team training improve team performance? A meta-analysis. Human Factors, 50(6), 903-933. https://doi.org/10.1518/001872008X375009
33. Shappell, S. A., & Wiegmann, D. A. (2000). The Human Factors Analysis and Classification System-HFACS (DOT/FAA/AM-00/7). Federal Aviation Administration.
34. Sneddon, A., Mearns, K., & Flin, R. (2013). Stress, fatigue, situation awareness and safety in offshore drilling crews. Safety Science, 56, 80-88.
35. Stanton, N. A., Salmon, P. M., Rafferty, L. A., Walker, G. H., Baber, C., & Jenkins, D. P. (2013). Human factors methods: A practical guide for engineering and design (2nd ed.). Ashgate.
36. U.S. Chemical Safety and Hazard Investigation Board. (2007). Investigation report: Refinery explosion and fire, BP, Texas City, Texas, March 23, 2005 (Report No. 2005-04-I-TX).
37. U.S. Chemical Safety and Hazard Investigation Board. (2009). Investigation report: T2 Laboratories, Inc. runaway reaction, Jacksonville, Florida, December 19, 2007 (Report No. 2008-03-I-FL).
38. U.S. Chemical Safety and Hazard Investigation Board. (2014). Investigation report: Catastrophic rupture of heat exchanger, Tesoro Anacortes Refinery, Anacortes, Washington, April 2, 2010 (Report No. 2010-08-I-WA).
39. U.S. Chemical Safety and Hazard Investigation Board. (2015). Investigation report: Chevron Richmond Refinery pipe rupture and fire, Richmond, California, August 6, 2012 (Report No. 2012-03-I-CA).
40. U.S. Chemical Safety and Hazard Investigation Board. (2018). Investigation report: Organic peroxide decomposition, release, and fire at Arkema Crosby following Hurricane Harvey, Crosby, Texas (Report No. 2017-08-I-TX).

41. U.S. Chemical Safety and Hazard Investigation Board. (2019). Investigation report: Toxic chemical release at the DuPont La Porte chemical facility, La Porte, Texas, November 15, 2014 (Report No. 2015-01-I-TX).
42. U.S. Chemical Safety and Hazard Investigation Board. (2022). Investigation report: Explosion and fire at the Husky Superior Refinery, Superior, Wisconsin, April 26, 2018 (Report No. 2018-02-I-WI).
43. Wiegmann, D. A., Zhang, H., von Thaden, T. L., Sharma, G., & Mitchell, A. A. (2004). Safety culture: An integrative review. The International Journal of Aviation Psychology, 14(2), 117-134.
44. Zohar, D. (1980). Safety climate in industrial organizations: Theoretical and applied implications. Journal of Applied Psychology, 65(1), 96-102. https://doi.org/10.1037/0021-9010.65.1.96