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A MATRIX-BASED PERSPECTIVE ON PSM ELEMENT INTEGRATION

Khairiah Mohd Mokhtar[1], Mohd Azimie bin Ahmad[2],
Taram Satiraksa Wan Abdullah[3] and Noor Diana Abdul Majid[4*]

[1]Faculty of Industrial Sciences and Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia
[2]School of Engineering and Technology, University of Technology Sarawak, No 1, Jalan Universiti, 96000, Sibu, Sarawak, Malaysia
[3]HSE Department, Ping Petroleum Sdn. Bhd., Menara Ilham, Level 32 Jalan Binjai, 50450 Kuala Lumpur, Malaysia
[4]Chemical Engineering Department, Universiti Teknologi PETRONAS, Persiaran UTP, 32610 Seri Iskandar, Perak, Malaysia

*Corresponding author: diana.majid@utp.edu.my

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ABSTRACT

Process Safety Management (PSM) plays a crucial role in preventing or reducing the risk of catastrophic releases of hazardous chemicals, which can lead to significant health consequences, fires, explosions, and loss of life. Historical industrial disasters such as the Texas BP refinery explosion highlight the critical need for robust and integrated PSM systems to prevent both human and financial losses. Effective implementation of PSM hinges on the integration of its constituent elements. While literature emphasizes interconnections among PSM components outlined in OSHA's 29 CFR 1910.119, a systematic mapping of these interrelationships remains underexplored. This study presents a matrix-based approach to visualize and analyze the integration of seven critical PSM elements: Employee Participation (EP), Contractor Management (CONC), Hot Work Permits (HWP), Incident Investigation (II), Emergency Planning and Response (EPR), Compliance Audit (CA), and Trade Secrets (TS). The matrix was constructed using regulatory mandates, evidence from scholarly literature and industry guidelines. The results identify EP and CONC as central integration nodes, demonstrating the highest degree of interconnectivity and frequent citation in OSHA enforcement records. These findings underscore the importance of coordination, information flow, and organizational learning in sustaining effective PSM implementation. From a practical perspective, the proposed matrix offers a diagnostic tool for safety managers to support PSM audits, contractor oversight, training design, and the development of integration-focused digital safety dashboards.

Keywords: Process safety management, OSHA, integration, matrix analysis, risk mitigation, employee participation

1.0 INTRODUCTION

Process Safety Management (PSM) is a comprehensive framework designed to prevent the accidental release of hazardous chemicals in industrial operations. The U.S. Occupational Safety and Health Administration (OSHA) formalized this approach through its Process Safety Management Standard (29 CFR 1910.119), which outlines 14 interrelated elements essential for maintaining safe operations. While each element serves a unique

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function, their effectiveness relies significantly on how well they are integrated and coordinated across organizational structures and operational layers [1].

Industrial accidents such as the Deepwater Horizon oil spill (2010), Tianjin storage facility explosion in Tianjin, China (2015), Visakhapatnam gas leak (2020) and Beirut port ammonium nitrate explosion (2020) have reaffirmed the catastrophic risks of fragmented safety systems. These events highlight the need to move beyond compliance and toward systems-thinking in safety management [2], [3]. Previous literature has explored PSM implementation success factors and highlighted interdependencies among selected elements such as Process Safety Information (PSI), Mechanical Integrity (MI), Pre-startup Safety Review (PSSR), Management of Change (MOC), Emergency Planning and Response (EPR), Contractor Management and Hot Work Permit [4], [5], [6], [7], [8], [9], [10]. However, a comprehensive matrix-based analysis that captures multidirectional relationships across a broader range of PSM elements remains underexplored.

Systems theory suggests that safety in complex operations emerges not just from the performance of individual elements, but from the dynamic interactions between them [11], [12]. Poor coordination, especially during transitions like maintenance, emergency response, or process modification can result in data silos, delayed risk communication, or conflicting procedures [13]. Such system-level vulnerabilities can negate the benefits of individual element compliance and hinder real-time hazard mitigation [14].

Despite more than three decades of implementation, major industrial accidents continue to occur in facilities that formally comply with Process Safety Management (PSM) requirements. Investigations of events such as Deepwater Horizon, Tianjin, and Beirut consistently reveal that failures rarely stem from the absence of individual PSM elements, but rather from poor coordination, weak information transfer, and fragmented implementation across elements. This highlights a fundamental limitation of compliance-driven PSM practices, which often treat elements as independent checklists rather than as components of an interconnected safety system.

Existing PSM research has predominantly focused on technically intensive elements such as Process Hazard Analysis (PHA), Mechanical Integrity (MI), and Management of Change (MOC). While these studies provide valuable insights, they often underemphasize elements that function as integration enablers, including Employee Participation (EP), Contractor Management (CONC), Incident Investigation (II), and Emergency Planning and Response (EPR). These elements play a critical role in facilitating communication, learning, and organizational alignment, yet their interactions with other PSM components are rarely examined in a systematic manner.

Furthermore, regulatory guidance outlines interdependencies among PSM elements, but does not provide a structured mechanism to visualize or evaluate the strength of these relationships. As a result, organizations may achieve nominal compliance while remaining vulnerable to systemic failures arising from weak inter-element integration. This gap underscores the need for an analytical approach that explicitly maps and evaluates how PSM elements interact as a system, rather than how they perform in isolation.

To address this gap, the present study proposes a matrix-based perspective to systematically examine the integration among selected PSM elements. By focusing on elements with high interaction potential and enforcement relevance, the study aims to make integration pathways visible, identify central coordination nodes, and provide a practical diagnostic tool for improving process safety performance.

2.0 METHODOLOGY

This study adopts a qualitative, matrix-based analytical approach to examine the integration among selected elements of the Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) framework (29 CFR 1910.119) [15]. The purpose of the methodology is to explicitly identify and structure inter-element relationships, thereby enabling a system-level understanding of PSM implementation beyond individual element compliance. To enhance clarity and transparency, the methodology adopted in this study follows a structured, stepwise framework designed to systematically identify and analyze inter-element integration within the OSHA PSM system. The methodological process comprises four sequential steps**,** as summarized in Figure 1.

2.1 Conceptual Framework for PSM Element Integration

To support the methodological design of this study, a conceptual framework is introduced to illustrate the positioning of selected Process Safety Management (PSM) elements within the broader PSM system. As shown in Figure 2, the PSM system can be viewed as comprising two interdependent layers: (i) a technical and operational control layer, and (ii) an information, coordination, and governance layer.

The technical and operational layer includes elements such as Process Safety Information, Process Hazard Analysis, Operating Procedures, Training, Mechanical Integrity, Management of Change, Pre-Startup Safety Review, and Hot Work Permit, which primarily function as engineered or procedural safeguards. In contrast, the information and coordination layer comprise elements that enable communication, learning, oversight, and alignment across the PSM system, including Employee Participation, Contractor Management, Incident Investigation, Emergency Planning and Response, Compliance Audit, and Trade Secrets.
This conceptual distinction guided the selection of PSM elements examined in this study and informed the subsequent identification of inter-element linkages. By positioning the selected elements within an information-centric layer, the framework provides a rationale for adopting a matrix-based approach to explicitly examine integration pathways between organizational and technical components of PSM implementation**.**

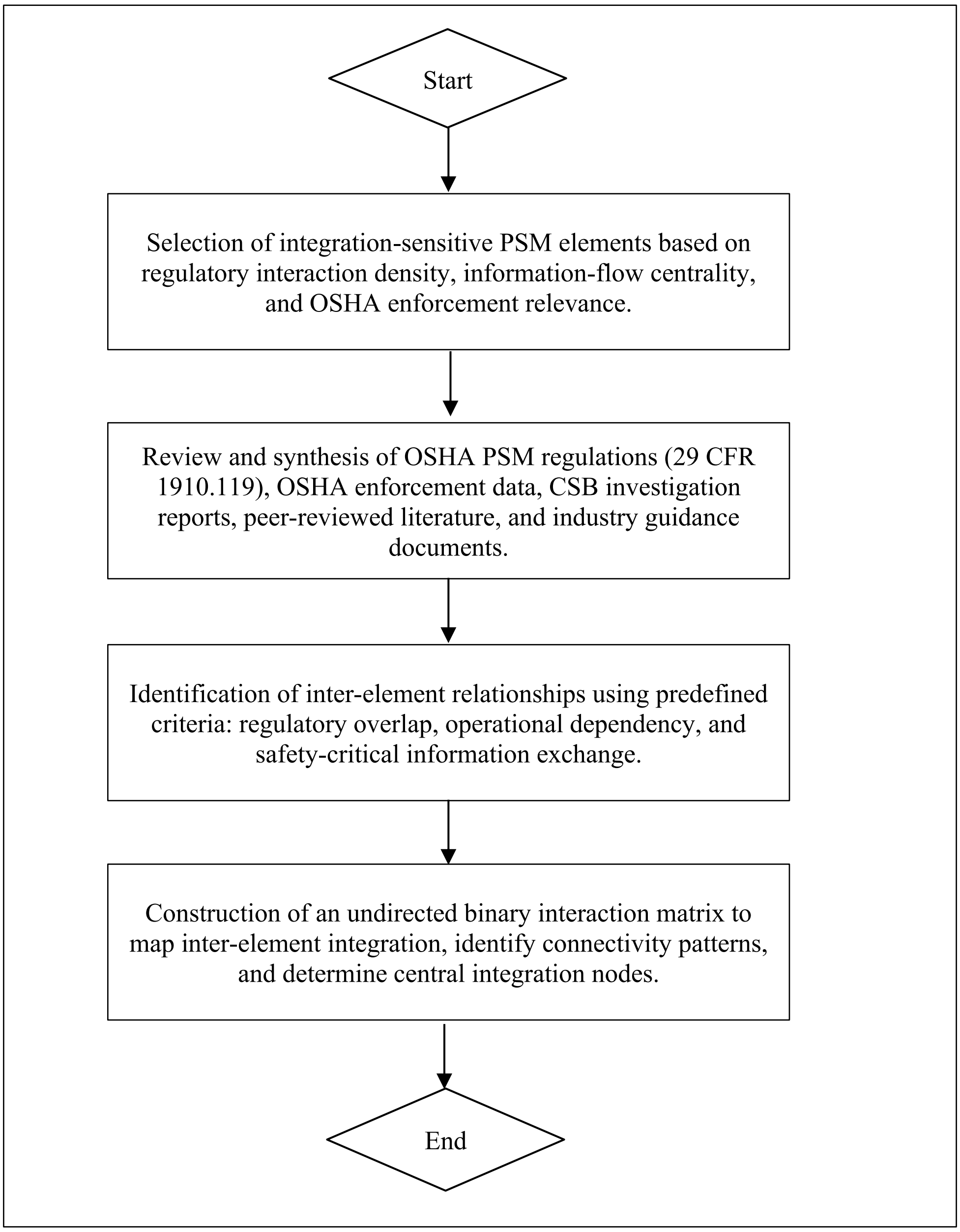

Figure 1. Methodological Framework for Matrix-Based PSM Element Integration Analysis

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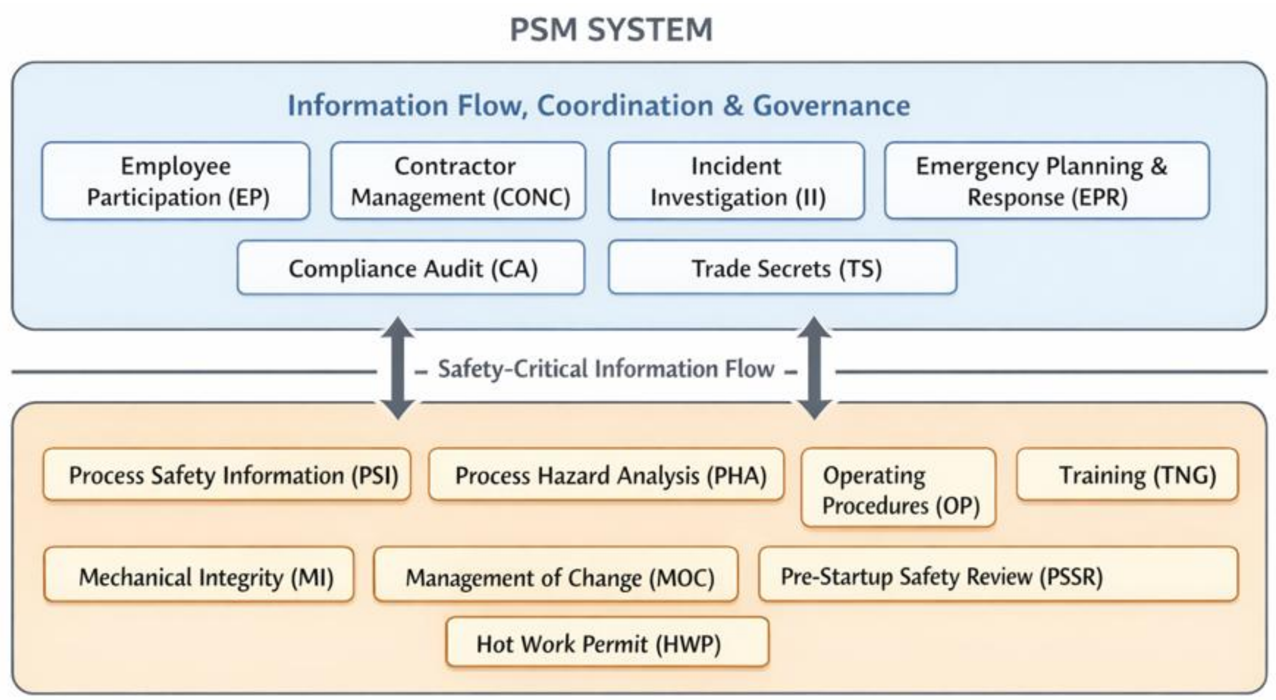

Figure 2. Conceptual positioning of selected PSM elements within the PSM system.

Figure 2 illustrates the distinction between technical and operational PSM elements and integration-sensitive elements that primarily function through information flow, coordination, and governance. The seven elements examined in this study are positioned within the information and coordination layer, reflecting their role in linking technical controls, workforce actions, and management oversight across the PSM system.

Conceptually, the selected PSM elements operate primarily within an information and coordination layer of the PSM system, interfacing between technical controls, workforce actions, and management oversight. As illustrated in Figure 2, these elements enable communication, learning, and alignment across traditionally siloed technical functions. Positioning the selected elements in this manner highlights their integration-sensitive nature and motivates the use of a matrix-based approach to examine their interdependence.

2.2 Selection of PSM Elements and Scope Definition

The selection of PSM elements was guided by the conceptual framework illustrated in Figure 2, which emphasizes integration-sensitive elements operating within the information and coordination layer of the PSM system. Seven PSM elements; Employee Participation (EP), Contractor Management (CONC), Hot Work Permit (HWP), Incident Investigation (II), Emergency Planning and Response (EPR), Compliance Audit (CA), and Trade Secrets (TS) were selected based on their historical citation frequency in OSHA enforcement data [16] and their commonly under-explored roles in inter-element integration studies [17]. These elements were selected due to their high interaction potential and critical influence on communication and safety information flow.

While OSHA's PSM framework comprises fourteen elements, this study intentionally focuses on a subset of seven elements to enable a deeper examination of integration mechanisms. Elements such as Process Hazard Analysis (PHA), Mechanical Integrity (MI), Management of Change (MOC), Operating Procedures (OP), Training (TNG), Pre-Startup Safety Review (PSSR), and Process Safety Information (PSI) were not selected as primary elements because their roles and performance metrics have been extensively examined in existing PSM literature [18] and regulatory guidance. Moreover, these elements are predominantly technical or procedural in nature, with integration roles that are comparatively well-defined and prescriptive under OSHA regulations.

In contrast, the selected elements—Employee Participation, Contractor Management, Incident Investigation, Emergency Planning and Response, Compliance Audit, Hot Work Permit, and Trade Secrets, function primarily as organizational, coordination, or information-bridging elements. These elements rely heavily on interaction with multiple other PSM components to be effective and are therefore more sensitive to integration quality. Focusing on these elements allows the study to address a documented gap in PSM research, where system-level coordination and information flow failures are frequently identified in major accident investigations but remain insufficiently mapped in existing frameworks.

2.3 Data Sources and Literature Synthesis

The interrelation analysis was informed by multiple authoritative sources, including:

- OSHA's PSM regulatory text (29 CFR 1910.119) [15]
- OSHA enforcement and citation summaries (1992–2023) [19]
- U.S. Chemical Safety Board (CSB) investigation reports [3]
- Peer-reviewed journals [11], [17]
- Industry guidance documents (e.g., CCPS, API, DOE) [20]

A targeted literature review was conducted using Scopus, Web of Science, and Google Scholar with search terms such as "PSM element interaction," "employee participation in safety," and "hot work interdependencies." Only English-language publications from 2000–2024 were included. The dataset used for this study comprised regulatory documents, enforcement summaries, accident investigation reports, and peer-reviewed literature related to Process Safety Management (PSM). Specifically, OSHA enforcement summaries and citation records spanning 1992 to 2023 were reviewed to identify recurring integration-related deficiencies across industries covered under the PSM standard. In addition, U.S. Chemical Safety Board (CSB) investigation reports involving major hazard facilities were examined. The literature review initially identified over 60 sources, from which 32 key publications were retained for detailed analysis based on predefined inclusion criteria.

Inclusion criteria for literature and regulatory sources required explicit relevance to PSM implementation, regulatory interpretation, accident investigation, or inter-element coordination within major hazard industries. Sources were required to either (i) provide empirical evidence, (ii) present post-incident analysis, or (iii) offer authoritative regulatory or industry guidance directly linked to one or more PSM elements. Exclusion criteria included purely descriptive safety management texts without reference to PSM integration, studies unrelated to process industries, and publications lacking substantive discussion of organizational, informational, or coordination aspects of PSM.

OSHA enforcement summaries and CSB investigation reports were analyzed qualitatively, focusing on case narratives and findings to identify recurring themes related to inter-element coordination and integration failures rather than conducting quantitative citation frequency analysis

2.4 Definition of Inter-Element Relationships

Inter-element relationships were identified by examining the functional role and regulatory intent of each selected PSM element. A link between two elements was established when at least one of the following conditions was satisfied:

- Regulatory overlap, where OSHA requirements explicitly link one element to another;
- Operational dependency, where the effective execution of one element relies on inputs from another; or
- Information exchange, where safety-critical information generated by one element must be communicated to another to prevent or mitigate hazards.

These criteria provide a transparent and reproducible basis for identifying interdependencies.

2.5 Matrix Construction and Binary Logic Approach

A binary logic approach was employed to operationalize inter-element integration within the matrix. An inter-element "link" was defined as present when at least one of the following conditions was satisfied:

i. Regulatory overlap, where OSHA requirements explicitly require interaction between two elements;
ii. Operational dependency, where effective implementation of one element relies on outputs from another; or
iii. Safety-critical information exchange, where information generated by one element must be communicated to another to prevent or mitigate hazards.

Initial identification of inter-element linkages was conducted by the authors through systematic examination of regulatory texts, enforcement interpretations, and supporting literature. Each identified relationship was coded as either present (√) or absent, based on convergence between regulatory requirements, enforcement interpretations, and supporting literature evidence.

Given the qualitative and conceptual nature of the study, formal inter-rater reliability testing was not applied; however, reliance on converging regulatory and literature evidence served as an implicit validation mechanism. The resulting relational matrix (Table 1) constitutes the core output of the methodological framework and forms the basis for subsequent analysis and discussion.

The resulting integration matrix is undirected (symmetric), meaning that an identified linkage between two PSM elements represents mutual interdependence rather than a directional or causal relationship (e.g., EP→PHA versus PHA→EP). This approach reflects the intent of the study to visualize coordination and information exchange pathways across the PSM system, rather than to model process sequence or cause–effect relationships. Directional or weighted matrices are acknowledged as valuable extensions and are proposed as future work for more detailed, industry-specific analyses.

2.6 Methodological Limitations

The analysis is qualitative in nature and relies on expert interpretation of regulatory and literature evidence. While the binary matrix effectively visualizes interdependencies, it does not capture relative interaction strength. To address this limitation, a weighted interaction scoring system is proposed as a future extension for industry-specific applications.

3.0 RESULTS AND DISCUSSION

To explicitly visualize the integration among PSM elements, a relational matrix was developed, as presented in Table 1. In this matrix, rows represent the selected PSM elements under investigation, while columns represent the remaining OSHA PSM elements. A marked cell (√) indicates the presence of a verified inter-element relationship based on regulatory requirements, operational dependency, or safety-critical information exchange.

The relational matrix developed for this study identifies the degree of interconnectivity among the selected PSM elements as shown in Table 1. EP and CONC are demonstrated as the most integrated elements, each directly linked to 13 and 12 of OSHA's 14 core PSM components, respectively. These are followed by II (8), EPR (7), CA and TS (6), and HWP (5). The centrality of EP and CONC positions them as key drivers of communication, risk awareness, and safety governance. This is further supported by OSHA citation data as illustrated in Table 2, where EP and CONC accounted for 10% and 9% of violations in the early years post-regulation (1992–1995), highlighting persistent challenges in implementing these elements. Additionally, the high degree of connectivity suggests that both EP and CONC act as foundational pillars for effective communication, information flow, and cross-functional coordination, aligning with OSHA's citation trends and reinforced by CSB's Deepwater Horizon findings [11]. Detailed explanation of interrelation specifically for EP, CONC, HWP, II, EPR, CA and TS elements were tabulated in Tables (3–9), respectively.

Table 1: PSM Matrix for EP, CONC, HWP, II, EPR, CA and TS Elements with other PSM Elements

	Employee Participation (EP)	**Process Safety Information (PSI)**	**Process Hazards Analysis (PHA)**	**Operating Procedures (OP)**	**Training (TNG)**	**Contractors (CONC)**	**Pre-Startup Safety Review (PSSR)**	**Mechanical Integrity (MI)**	**Hot Work Permit (HWP)**	**Management of Change (MOC)**	**Incident Investigations (II)**	**Emergency Planning and Response (EPR)**	**Compliance Audit (CA)**	**Trade Secret (TS)**
EP		√	√	√	√	√	√	√	√	√	√	√	√	√
CONC		√	√	√	√		√	√	√	√	√	√	√	√
HWP		√	√	√	√			√						
II	√	√		√	√	√		√				√	√	
EPR		√	√	√	√			√			√		√	
CA		√			√			√	√	√		√		
TS		√	√	√							√	√	√	

From the matrix, EP and CONC elements were often cited during the 36 months after the PSM OSHA effective date (May 26th, 1992) with 180 and 168 violations for EP and CONC respectively from 1843 violations which make up 10% and 9% of total violations correspondingly [21]. In the investigation report of Macondo/Deepwater Horizon Oil Rig Fire and Explosion, the U.S. Chemical Safety and Hazard Investigation Board (CSB) recommended that American Petroleum Institute (API) to revise API Practice 75. This involves in part, expanding the Safety and Environmental Management System (SEMS) responsibilities beyond just the operator and including explicit and expanded responsibilities for workforce involvement (employee participation) and contractor oversight. Thus, this proves that both employee participation and contractors are elements which are incredibly important to ensure that process safety is at the top notch to prevent catastrophic accidents. EP and CONC are central to safety information flow and participation. Their interrelations emphasize communication between management and frontline workers, and oversight of third-party risk.

Table 2: OSHA PSM Citations from May 1992 to May 1995 [21]

Subsection of Standard 29 CFR 1910.119	**Number of Violation**	**% of Total**
a) Operating Procedures (OP)	405	22
b) Mechanical Integrity (MI)	295	16
c) Training (TNG)	193	10
d) Employee Participation (EP)	180	10
e) Contractors (CONC)	168	9
f) Process Hazards Analysis (PHA)	165	9
g) Process Safety Information (PSI)	151	8
h) Management of Change (MOC)	125	7
i) Incident Investigation (II)	59	3
j) Emergency Planning and Response (EPR)	51	3
k) Hot Work Permit (HWP)	29	2
l) Pre- Startup Safety Review (PSSR)	19	1
m) Compliance Audit (CA)	3	--
n) Trade Secret (TS)	0	--
Total for all 14 Subsections	1843	100

Table 3: Interrelations of EP Element

PSM Element	Interrelates Elements	Details
EP	PSI	• Maintenance personnel, operators and other staff perform field checks to verify information for inclusion in the PSI.
	PHA	• Participation in developing and conducting PHA on the various covered process areas. • The results of the PHA are shared with employees impacted by the findings and recommendations.
	OP	• Consultation to supply input on various process using or maintenance procedures. • Procedures are developed based on employee knowledge and experience. • Critiques and implements new processes and procedures.
	TNG	• Newly assigned personnel should be introduced to the employee participation program as an integral part of their initial PSM system training. • Consultation on PSM training programs that include the need to conduct refresher training on an existing covered process. • Develop and deliver training.
	CONC	• Provide guidance on specific hazards associated with their tasks or any risks encountered in their work.
	PSSR	• Operators, maintenance personnel and other personnel take part in PSSR. • Raise any concerns that were not addressed during the PSSR.
	MI	• Operations and maintenance personnel supply input for equipment history and reliability, records saw data, keep inspection and maintenance database. • Review and comment on manufacturer's recommendation and equipment failure and make recommendations for change.
	HWP	• Operations and maintenance personnel are responsible for planning and implementing safe work procedures as documented in the hot work permits.
	MOC	• Operations and maintenance personnel are tasked with developing and executing safe work procedures outlined in the hot work permits.
	II	• Investigations are carried out by teams comprising a diverse range of workforce members, including non-management employees. • Management is responsible for addressing, resolving, and executing the findings and recommendations detailed in the investigation report. • Incident investigations result of are conveyed to the relevant personnel.
	EPR	• ERT are composed of a diversified group of employees, not to be missed non-management staff, ensuring representation across the workforce. • Critiques on drills and on-site emergency response plan. • Communication with workers to promote understanding of the actions to take during emergencies.
	CA	• Operators, maintenance personnel, and other staff participate in the PSM system audit.
	TS	• Workers seeking access to trade secret information sign confidentiality agreements before being given access to such information.

As detailed in Table 3, EP element has links with all 13 other elements of OSHA PSM. The identified relationships of EP element with other PSM elements were a combination of information gathered from literatures [11], [12], [13]. EP, also referred to as Workforce Involvement, is recognized as one of the most critical elements in the PSM standard. Its significance lies in the active involvement of employees at every organizational level, which is essential for the success of any PSM program. Employees across various roles and positions bring unique responsibilities, expertise, and insights that contribute to the build-out, implementation, and constant enhancement of the process of safety management system, ultimately ensuring the safe operation of the organization [14].

The EP element facilitates a two-way exchange of information between management and employees,

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aimed at providing critical process safety details to avoid or minimize the risks of disastrous releases of hazardous substances in the workplace. While management is responsible for disseminating this information, it is equally important for them to actively seek input and collaboration from employees in the buildout and refinement of PSM programs [16], [19]. Employees possess the most in-depth knowledge regarding the daily operation of processes and the maintenance of equipment and facilities. A written plan of action needs to be developed by the management detailing exactly how employees can aid in the PSM program development and to ensure the uniform implementation of PSM activities across their organization [16], [22]. The management needs to have due and fair consideration of the input given by employees for the success of employee participation.

The analysis of the interrelation between the CONC element and other PSM elements was conducted in a manner like the study on EP element interrelations. This involved examining the objectives and functions of the CONC element as outlined in OSHA PSM requirements. The identified relationships between the CONC element and other PSM components were derived from a combination of information obtained from relevant literature [11], [12], [13]. Table 4 sets out the interrelations of CONC element with other elements of PSM.

The matrix-based analysis demonstrates that CONC is one of the most highly interconnected PSM elements, exhibiting linkages with 12 other PSM elements. This high degree of connectivity highlights CONC's role as a critical integration interface within the PSM system. Under OSHA requirements, it is the responsibility of the employer to ensure that contractors working in, and around hazardous chemicals possess the appropriate skills, knowledge, and experience to perform their tasks without compromising process safety [23]. The extensive interdependencies identified in the matrix reflect this regulatory expectation and emphasize that contractor safety cannot be managed in isolation.

In particular, the TNG element of PSM plays a pivotal role in supporting effective contractor integration. Contractor training must, at a minimum, address HWP requirements, hazards associated with the work area prior to job initiation, and the risk mitigation measures identified through PHA. Training should also include recognition of alarms and warning signs of abnormal conditions, as well as appropriate actions to be taken during emergencies in accordance with the facility's EPR arrangements [22], [24]. These requirements are summarized in Table 4, which consolidates the PSM-related obligations applicable when contractors are engaged at a facility.

The importance of CONC is further amplified by increasing outsourcing trends in process industries, where maintenance, inspection, turnaround, and specialized operations are frequently performed by third-party contractors. Empirical studies have shown that outsourced operations are associated with a higher incidence of fatal and major accidents, largely due to deficiencies in communication, misalignment of training, and unclear allocation of safety responsibilities [25]. Consistent with these findings, the matrix reveals strong interdependencies between CONC and elements such as EP, TNG, II, and EPR. Weak integration across these linkages has been repeatedly identified in major accident investigations as a contributing factor to process safety failures.

The central role of CONC identified in this study is strongly supported by published research on PSM implementation in contractor-intensive process plants [10]. Previous studies report that contractors are frequently engaged in high-risk activities—including maintenance, shutdowns, and hot work—yet often operate with limited access to site-specific hazard information and safety systems [25], [26]. As a result, effective PSM implementation requires contractors to be fully embedded within core PSM elements rather than managed through isolated administrative controls. Deficiencies in contractor integration have been consistently linked to major industrial accidents, particularly where communication of process hazards, permit requirements, and emergency procedures between host organizations and contractors is fragmented [9], [22].

The linkage between Contractor Management and Emergency Planning and Response is especially critical in meeting minimum PSM requirements [9], [10]. OSHA regulations explicitly require that contractors be informed of emergency action plans and participate in emergency preparedness activities (29 CFR 1910.119(h); 29 CFR 1910.38). However, accident investigations have shown that contractors often lack familiarity with site-specific alarms, evacuation routes, and response protocols, resulting in delayed or ineffective emergency response [19]. The strong CONC–EPR linkage identified in the matrix therefore reflects a well-documented regulatory and operational requirement: emergency preparedness cannot be considered effective or compliant unless contractors are fully integrated into EPR planning, training, and drills.

Overall, the prominence of Contractor Management within the matrix reinforces the view that CONC functions as a key interface between operational execution and system-level safety governance. By explicitly mapping these relationships, the matrix-based analysis extends existing contractor-focused PSM studies by providing a structured visualization of how Contractor Management interacts with multiple PSM elements, and how weaknesses in contractor integration can undermine both routine operations and emergency response performance.

Table 4: Interrelations of CONC Element

PSM Element	Interrelates Elements	Details
CONC	PSI	• Supply access and information to PSI for the processes where contractors work.
	PHA	• Supply access to PHA for the processes where contractors work. • Address hazards and risks of their work location.
	OP	• If contractors are employed as operators, they must follow and apply the established operating procedures.
	TNG	• Equipped with the necessary training to effectively carry out the tasks for which they are hired. • Equipped to properly implement safe work practices. • Training would be provided in emergency response plans and trained as emergency responders. • Refresher training for long-term contractors. • Contractor training responsibilities are divided between the contractor's employer, who provides specific job-related training, and the plant employer, who ensures site-specific, and safety protocols are covered.
	PSSR	• Contractors frequently contribute to completing the Pre-Startup Safety Review (PSSR) during equipment or facility changes.
	MI	• Perform preventive and corrective maintenance in plant. • Contribute to the design and installation phases of engineering projects.
	HWP	• Contractors must adhere to the conditions of the Hot Work Permit (HWP) for all tasks performed at a facility and may also participate in the completion and approval process of the HWP.
	MOC	• Contractors affected by workplace changes must be notified and provided with appropriate training to address those changes.
	II	• Contractors must response to incidents and near misses involving their activities. • II should involve contractors when they have been directly affected in an incident or a near-miss event.
	EPR	• Training the contractors on the relevant requirements of the emergency action plan and may assigned in emergency response roles.
	CA	• Confirm whether the contractor safety program and performance information were reliably obtained and thoroughly reviewed during the selection process. • Audit should decide whether waivers were properly authorized. • Records should be kept for reference when making selections for future contracts.
	TS	• Protection of proprietary information – execution of confidentiality agreements.

In contrast to the strategic and coordination-focused roles of EP and CONC, the HWP element shown in Table 5 functions as a task-specific safety control, interacting primarily with technical PSM elements such as PSI, PHA, OP, MI, and TNG. These relationships, derived from established literature, ensure that hazardous maintenance and non-routine activities involving ignition sources are conducted within clearly defined and controlled boundaries [26], [27], [28]. The HWP system aims to ensure that hazards have been properly analyzed and risks mitigated through accurate technical inputs from PSI, PHA, and OP, while the TNG element ensures that personnel executing the work understand site-specific hazards and required safety measures. MI further supports HWP implementation by identifying when hot work is necessary and ensuring that associated equipment, isolation systems, and protective devices are adequately maintained.

Although HWP exhibits lower overall interconnectivity compared to organizational elements in the matrix, its significance is underscored by its role as a primary protective barrier against ignition-related incidents. Historical accident investigations, including refinery tank fires and offshore maintenance incidents, have repeatedly demonstrated that failures in hot work control—such as inadequate gas testing, ineffective isolation, or incomplete communication of permit conditions—can rapidly escalate into major accidents when upstream integration is weak [29], [30], [31]. The effectiveness of HWP is therefore strongly dependent on its integration with organizational elements, particularly EP and CONC. Limited employee participation may result in permit systems being treated as administrative formalities rather than active safety controls, while inadequate contractor integration can lead to contractors being unfamiliar with site-specific hazards, permit limitations, or emergency response actions. As a result, even small deficiencies in information dissemination, verification, or procedural adherence can lead to significant safety implications, reinforcing the characterization of HWP as a localized yet high-risk element within the PSM framework.

Table 5: Interrelations of HWP Element

PSM Element	Interrelates Elements	Details
HWP	PSI	• Accurate equipment recognition, lockout/tagout (LOTO), and MSDS data are vital for the effective execution of HWP.
	PHA	• Address hazards and risks of the hot work area.
	OP	• OPs require that specific safe work practices be established, and these practices serve to complement the guidelines outlined in the SOPs.
	TNG	• Operators must receive comprehensive training in safe work practices and hazard recognition.
	MI	• Safe performance of all repair and maintenance activities relies on the implementation of lockout/tagout, confined space entry, line breaking, and other established safe work practices. • Maintenance personnel must receive comprehensive training in safe work practices.

As shown in Table 6, II exhibits direct interrelations with eight other PSM elements, underscoring its role as a central organizational learning mechanism within the PSM system. The matrix indicates that II acts as a catalyst for corrective actions and system updates, particularly influencing OP, MI, TNG, and EPR. This finding is consistent with prior studies identifying incident learning as a critical feedback loop for continuous improvement in safety management systems [22]. The observed interdependencies are further supported by OSHA requirements and literature-based analyses [25], [32], which emphasize II's reliance on PHA for structured root-cause identification and on EPR for securing incident scenes, preserving evidence, and enabling appropriate emergency activation.

A primary objective of II is to enable organizations to learn from incidents and near misses and to communicate lessons learned to both internal and external stakeholders [22], [23]. Effective incident investigation depends on active participation from employees and contractors, who frequently provide essential operational insights during investigations. Within this process, PHA contributes analytical rigor by identifying underlying hazards and failure mechanisms, while EPR supports evidence control and on-site coordination during and immediately following incidents. The outcomes of II commonly result in updates to PHA, OP, TNG, MI, and EPR, reinforcing its role as a cross-functional corrective and learning mechanism within the PSM framework.

In accordance with OSHA requirements under 29 CFR 1910.119(m), incident investigation findings must be retained for use in subsequent Process Hazard Analyses or for the minimum retention period specified by regulation, thereby supporting compliance auditing and organizational learning. However, the effectiveness of II as a learning mechanism is often constrained by organizational barriers such as blame-oriented safety cultures, fear of disciplinary action, and inadequate reporting of near misses. These barriers limit the completeness of incident data and weaken the strength of integration between II and other PSM elements, particularly TNG, OP, EP, and CA by reducing the translation of lessons learned into system-wide improvements. Poor dissemination of investigation outcomes further diminishes feedback loops, undermining II's role as a driver of continuous improvement. Addressing these barriers is therefore essential to strengthening the integrative function of Incident Investigation within the PSM system.

Table 6: Interrelations of II Element

PSM Element	Interrelates Elements	Details
II	EP	• Employees participate as members of the investigation team.
	PHA	• PHA as part of the investigation process for a process safety incident. • The findings of the investigation should be kept for use in the next PHA or for a minimum of 2 years, whichever is greater
	OP	• II findings frequently lead to modifications in operating procedures.
	TNG	• Supply awareness, refresher training, root cause analysis, forensics, investigation team and incident and near miss reporting/notification training. • II findings often lead to updates in the operator training program.
	CONC	• Contractors may report incidents and include them in investigations.
	MI	• Findings from II often lead to adjustments in the MI program, specifically in inspection, testing, and preventive maintenance practices.
	EPR	• Ensure preservation of evidence. • II findings occasionally lead to revisions in emergency plans or procedures.
	CA	• The findings of the investigation should be kept for use in the next company audits, or for a minimum of 2 years, whichever is greater

As illustrated in Table 7, EPR exhibits strong interrelations with multiple PSM elements, reflecting its role as a system-level safeguard designed to manage the consequences of abnormal and emergency conditions. The matrix highlights EPR's integration with PSI, PHA, II, TNG, CONC, and TS, underscoring its dependence on accurate hazard information, effective communication, and coordinated organizational response. These findings are consistent with regulatory requirements and prior studies that emphasize EPR as a critical element for mitigating escalation and minimizing harm during major accident scenarios [26], [33], [34].

Recent developments in emergency management practices, including digital alarm systems, computerized emergency response platforms, and real-time monitoring tools, have enhanced situational awareness and coordination during emergency events. However, their effectiveness depends on accurate hazard information, timely data availability, and alignment with established emergency procedures, reinforcing the need for strong integration between Emergency Planning and Response and upstream PSM elements [20], [35].

The relationship between EPR and TS represents a critical and often underexplored integration challenge. While the protection of proprietary information is necessary for commercial reasons, restricted access to chemical identity and hazard data can hinder emergency preparedness and response effectiveness. This tension becomes particularly evident during emergency situations where first responders and contractors require timely access to safety-critical information to make informed decisions [26], [36]. The matrix captures this dependency by highlighting how insufficient integration between EPR and TS can compromise emergency response planning, training, and execution.

In addition, the effectiveness of EPR is closely linked to CONC and TNG. Contractors and temporary workers are often less familiar with site-specific emergency procedures, alarm systems, and evacuation routes, increasing the risk of delayed or inappropriate response during emergencies. Integration of contractors into emergency drills, training programs, and communication protocols is therefore essential to ensure EPR meets minimum PSM requirements and functions effectively under real-world conditions [36], [37]. This finding aligns with accident investigation reports that identify inadequate contractor preparedness as a recurring weakness in emergency response performance.

Overall, the prominence of EPR within the matrix reinforces its role as a convergence point between hazard information, organizational learning, and operational execution. Weaknesses in integration, audiwhether due to technological limitations, information restrictions related to trade secrets, or insufficient contractor inclusion can significantly reduce the effectiveness of emergency response efforts. By explicitly mapping these interdependencies, the matrix-based approach provides a structured means of identifying vulnerabilities in EPR integration and prioritizing targeted improvements to strengthen emergency preparedness within the PSM framework.

Table 7. Interrelations of EPR Element

PSM Element	Interrelates Elements	Details
EPR	PSI	• Data/ knowledge is needed to structure an emergency response plan.
	PHA	• PHA will find hazard scenarios.
	OP	• Include emergency response plans while operating equipment.
	TNG	• In case of incidents, emergency responders are well trained for the emergency plan. • Basic requirements of recognizing emergencies, alarms, and the emergency action plan are to be trained to all employees, including contractors.
	MI	• Find emergency response and evacuation equipment that requires inspections, tests, preventive maintenance, or replacement activities.
	II	• Actual activation of the emergency action/emergency response plan will happen because of incidents.
	CA	• Periodical evaluation of emergency response management.

As reflected in the matrix, CA functions as a verification and governance mechanism that reinforces integration across the PSM system rather than operating as a standalone compliance exercise. CA exhibits interrelations with multiple elements, including II, TNG, OP, MI, and EPR, highlighting its role in confirming that corrective actions and procedural updates are effectively implemented and sustained over time [20], [33], [34]

The effectiveness of CA is closely tied to the quality of information flowing from upstream elements, particularly Incident Investigation. Findings from II inform audit scope and focus, while updates to OP, MI, and TNG provide measurable indicators of corrective action effectiveness. Process safety guidance emphasizes that recurring audit findings and delayed closure of action items are indicators of weak integration rather than isolated non-compliance issues [20].

Integration-focused performance indicators can be used to strengthen the practical application of CA, including metrics such as the number of audit findings involving cross-element deficiencies, average closure time for corrective actions affecting multiple PSM elements, and recurrence rates of previously identified integration gaps [20]. By mapping audit findings onto the integration matrix, organizations can prioritize improvement efforts toward interfaces with the greatest potential impact on risk reduction, reinforcing CA's role as an active mechanism for continuous improvement within the PSM framework.

Table 8. Interrelations of CA Element

PSM Element	Interrelates Elements	Details
CA	PSI	• The PSM program must be documented in accordance with the relevant RAGAGEPs for all processes and equipment.
	TNG	• Operators, maintenance personnel, and other affected staff should receive training in accordance with relevant laws and regulations, such as emergency response training under HAZWOPER regulations and compliance audit requirements.
	MI	• Assessment, checking, and preventive maintenance programs should adhere to the relevant RAGAGEPs when selecting MI tasks and determining their frequencies.
	HWP	• Adherence to any additional regulations that apply, such as OSHA's Lockout/Tagout Standard and fire protection requirements outlined in Section 1910.252(a), is required.
	MOC	• Address changes started by the standard system.

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	EPR	• Emergency response plans must fulfill with any extra governing procedures, such as OSHA's HAZWOPER regulations and the emergency action plan requirements specified in Section 1910.38(a).

The matrix-based analysis indicates that TS exhibits selective but critical interrelations with several PSM elements, particularly PSI, PHA, EPR, and II. While TS serves a legitimate role in protecting proprietary process information, excessive restrictions on information access can weaken integration strength when safety-critical data are not available for hazard analysis, emergency planning, or investigation activities [20].

Industrial examples from chemical manufacturing, mining operations involving proprietary reagents, and other process industries have demonstrated that limited disclosure of chemical identity and hazard information can delay hazard identification, complicate emergency response planning, and increase risks to emergency responders and contractors [29]. Accident investigations have further shown that restricted access to proprietary process information can hinder effective root cause analysis, thereby weakening the feedback loop between II and downstream elements such as TNG and OP [20], [29].

To mitigate these challenges, process safety guidance recommends the establishment of clearly defined trade secret disclosure protocols during PHA, EPR, and II activities, supported by standardized confidentiality agreements for investigators, auditors, regulators, and emergency responders [20]. These controls allow organizations to balance intellectual property protection with safety requirements while preserving integration across the PSM system.

Table 9. Interrelations of TS Element

PSM Element	Interrelates Elements	Details
TS	PSI	• All information must be available to those responsible for compiling the process safety information.
	PHA	• All necessary information must be provided to those developing the process of hazard analysis.
	OP	• All necessary information must be provided to those developing the operating procedures.
.	II	• All information necessary must be provided to those responsible for performing incident investigations.
	EPR	• All information must be available to those responsible for emergency planning and response.
	CA	• All information must be available to those responsible for compliance audits,

While the matrix in this study presents interrelations qualitatively, its effectiveness could be significantly enhanced by incorporating a weighted interaction matrix. A scoring system ranging from 0 (no link) to 3 (strong dependency) would enable organizations to more effectively prioritize their integration efforts and concentrate on essential linkages that are critical to their mission. Moreover, while EP and CONC appeared as the most interconnected components overall, the significance and influence of particular elements may differ across various industries. OSHA's sector-specific guidance, including that for petroleum refining or fertilizer manufacturing, emphasizes that factors such as Management of Change (MOC) and Pre-Startup Safety Review (PSSR) may hold more significant operational importance based on the complexity of processes and potential hazards [1]. This highlights the importance of adapting the matrix model to specific contexts.

The present analysis has also examined element interactions on an individual basis, which may overlook synergistic triads or feedback loops. The interdependency among CONC, II, and TNG presents a potential leverage point for enhancing contractor safety performance in high-risk environments. Identifying and examining these clusters can guide focused safety measures. Ultimately, although the matrix offers a strong conceptual foundation, its practical implementation requires complementary systems like maturity checklists, compliance dashboards, and digital PSM mapping platforms. Integrating this model into safety management software would improve accessibility, enable ongoing monitoring, and bolster decision-making processes.

Comparison with Published PSM Integration Studies

The integration patterns revealed by the proposed matrix are consistent with and extend findings reported in prior PSM studies and major accident investigations. Previous research has emphasized that organizational and human-centered elements play a critical role in sustaining effective PSM implementation, particularly through workforce involvement, communication, and learning mechanisms [11], [22]. The strong centrality of EP identified in this study aligns with these findings, reinforcing its role as a key enabler of cross-element communication, hazard awareness, and continuous improvement across the PSM system.

Similarly, the high degree of interconnectivity associated with CONC supports observations by Nenonen (2011) and findings from U.S. Chemical Safety Board (CSB) investigations, which repeatedly identify contractor coordination failures as contributing factors in major industrial accidents. While earlier studies have discussed contractor-related risks primarily in narrative or case-based forms, the matrix-based approach adopted in this study explicitly maps how Contractor Management interfaces with multiple PSM elements, including TNG, II, and EPR, thereby providing a more structured system-level representation [16], [25].

In contrast, HWP demonstrates lower overall connectivity within the matrix, which is consistent with its characterization in the literature as a localized yet high-risk control mechanism [22]. Accident investigations have frequently identified hot work as an ignition source when upstream integration such as inadequate hazard analysis, incomplete training, or insufficient contractor supervision is weak. The matrix highlights how failures in these upstream elements can directly compromise HWP effectiveness.

The role of II as a learning mechanism within the PSM system is also consistent with prior studies emphasizing feedback loops and organizational learning as essential components of process safety performance [22], [24]. The matrix extends this understanding by illustrating how II interacts with multiple downstream and upstream elements, including OP, TNG, MI, and EPR.

Compared to existing literature that typically examines PSM elements individually or through descriptive discussion, the proposed matrix consolidates these established insights into a visual and structured system-level framework. This enhances the interpretability and practical applicability of published findings by making interdependencies explicit and enabling targeted identification of integration gaps within the PSM system.

4.0 CONCLUSION

This study presents a matrix-based perspective on Process Safety Management (PSM) element integration, addressing a critical gap in conventional PSM implementation where elements are often managed as isolated compliance requirements rather than as an interconnected system. By systematically mapping interdependencies among selected PSM elements, the proposed matrix provides a structured means of visualizing integration strength and identifying critical interfaces that influence overall process safety performance.

The results demonstrate that organizational and coordination-focused elements—particularly Employee Participation (EP), Contractor Management (CONC), Incident Investigation (II), and Emergency Planning and Response (EPR)—exhibit high levels of interconnectivity and function as central nodes within the PSM system. In contrast, task-specific and technical controls such as Hot Work Permit (HWP) display lower overall connectivity but remain high-risk due to their dependence on upstream information quality and organizational integration. These findings highlight that process safety effectiveness is driven not only by the presence of individual PSM elements, but by the strength and quality of their interactions.

From a practical perspective, the matrix offers a diagnostic tool that can support safety managers, auditors, and practitioners in systematically assessing PSM integration within their facilities. Organizations can use the matrix to map existing inter-element linkages, identify weak or missing connections, and prioritize improvement actions. Strengthening integration among EP–CONC–II–EPR interfaces can yield significant improvements in both routine operations and emergency preparedness. The matrix framework is also adaptable for use in compliance audits, training program design, and digital PSM dashboards, enhancing its applicability across different organizational contexts.

This study has several limitations. The integration assessment is based on qualitative judgment derived from regulatory requirements and literature evidence, and the matrix is intentionally undirected, focusing on mutual interdependence rather than causal relationships. In addition, the analysis is grounded primarily in the U.S. OSHA PSM framework, which may limit direct applicability in jurisdictions with different regulatory structures. Future work could extend the framework by incorporating expert-based weighting schemes, directional or dynamic matrices, and quantitative validation using incident or audit data across diverse industrial sectors.

Overall, the matrix-based approach advances understanding of PSM as a system of interacting elements rather than a collection of standalone practices. By making integration pathways explicit, the proposed framework contributes a practical and scalable tool for enhancing process safety governance and supporting continuous improvement in complex process industries.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

ETHICS DECLARATION

This study did not involve human participants, animal subjects, or sensitive data. Consequently, formal ethical approval was not required.

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