

A Review of Process Safety Management Frameworks for Mechanical Systems

Mr. Kapil Ahir,
Assistant Professor,
Mandsaur University, Mandsaur
Department of Computer Sciences and Applications
kapil.ahir@meu.edu.in

To Cite this Article

Mr. Kapil Ahir, "A Review of Process Safety Management Frameworks for Mechanical Systems", *Journal of Science Engineering Technology and Management Science*, Vol. 03, Issue 05, May 2026, pp: 261-270, DOI: <http://doi.org/10.64771/jsetms.2026.v03.i05.pp261-270>

Submitted: 08-04-2026

Accepted: 12-05-2026

Published: 19-05-2026

Abstract—Process Safety Management (PSM) structures that are particularly focused on mechanical systems working in high-risk industrial settings. Mechanical systems, including pressure vessels, piping networks, rotating equipment, and structural components are used in harsh environment conditions, which is both mechanical and thermal, where failure may lead to disastrous s key regulatory and functional safety models, such as mechanical integrity schemes, risk assessment schemes, Safety Integrity Level (SIL) and lifecycle-based management systems. It examines how hazard identification, risk assessment, change management, reliability engineering, and asset integrity management are integrated into structured PSM systems of safety culture, evidence-based PSM, dynamic risk analysis, and practical implementation strategies, connection between the practice of mechanical engineering and process safety principles to guarantee the active reduction of risks. that good mechanical integrity, functional safety, and monitoring integration improve reliability, avoid loss of containment and improve the performance of the industrial safety in various sectors.

Keywords— Mechanical Integrity, Risk Assessment, Process Safety Management (Reliability Engineering, Hazard Analysis).

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I. INTRODUCTION

The reliability, safety, and profitability of manufacturing activities are crucial to their sustainability [1]. Mechanical systems are the physical basis of high-risk industrial systems, the interface between the design of a process and its actual operation[2]. Machinery like pressure vessels, piping systems, rotating machinery and heat exchangers are subject to such severe mechanical and thermal conditions that failure can quickly result in large-scale process accidents. Owing to the direct work with hazardous materials and energy, the reliability of these systems cannot be separated in terms of the overall process safety performance[3]. Therefore, their integrity cannot be taken up separately, but needs to be incorporated systematically into a structured Process Safety Management (PSM) that regulates the way in which hazards are recognized, managed, monitored.

Process Safety Management offers the organization and technical arrangement by which the risks of mechanical systems are addressed in a proactive and not a reactive manner[4]. Businesses can benefit from process safety management (PSM) practices when enough safeguards are in place to ensure the safe, effective, reliable, and profitable operation of the firm. Among PSM's basic principles is mechanical integrity, which unites a unified strategy for safety by correlating engineering design, operational discipline, inspection, and maintenance. Nonetheless, to uphold mechanical integrity going beyond adherence to codes and standards, it is necessary to ensure ongoing assessment of the possible failure mechanisms risk assessment as the analytical linkage between the behavior of mechanical systems and the decision-making processes in the PSM.

Risk assessment techniques like hazard analysis, failure mode analysis and risk-based inspection allow organizations to take a systematic analysis on how the processes of mechanical degradation, namely corrosion, fatigue, creep, erosion and vibration, could undermine system operation. Risk assessment can be used to support prioritized change of maintenance, optimized inspection, and rational decision-making of changes by quantifying likelihood and consequence[5]. By so doing, it converts mechanical integrity as a normal maintenance process into a dynamic data-based part of Process Safety Management. This integration makes sure that the risk controls evolve as the equipment keeps getting old, operations keep changing, and new hazards[6]. A lifecycle-based safety culture is formed through the successful combination of mechanical systems, Process Safety Management, and risk assessment. Between inherently safer design at the project development phase, and predictive maintenance and performance monitoring at the operation phase.

A. Structure of the paper

The paper structure is as follows: Section II: A study of the main process safety management system's framework. Section III: How the design and function of a mechanical system affects process safety Section IV talks about how to combine process safety management with the work of mechanical engineers. Section V: Review of the literature; Section VI: Conclusions and plans for future work.

II. FRAMEWORK ANALYSIS OF MAJOR PROCESS SAFETY MANAGEMENT SYSTEMS

The Process Safety Management (PSM) systems offer methodical and organized methods to avoid disastrous events in the high-risk sectors[7]. Management best practices, functional safety specifications, mechanical integrity schemes, risk assessment methods, and regulatory requirements are the main components of these frameworks. Systems based on regulations, such as OSHA PSM, govern compliance, documentation, process hazard analysis, and change management; systems based on functional safety standards, on the other hand, address SIL and the dependability of safety monitored systems. Risk-based strategies such as reliability-centered maintenance and risk-based inspection improve further the integrity of assets and operational reliability.

A. Regulatory-Based Process Safety Management Frameworks

Process Safety Management frameworks based on regulations set obligatory safety measures to avoid big industrial mishaps with dangerous processes. These models place an emphasis on governance of change, process hazard analysis, mechanical integrity, conformity with regulatory standards, and organized documentation to provide systematic control of risks and accountability across the organization.

1) OSHA PSM Structure

PSM is a program that OSHA put together in response to the growing number of serious accidents that occur in the process industries [8]. PSM framework for an already-established PSM system; specific OSHA PSM component. Show in Figure 1.

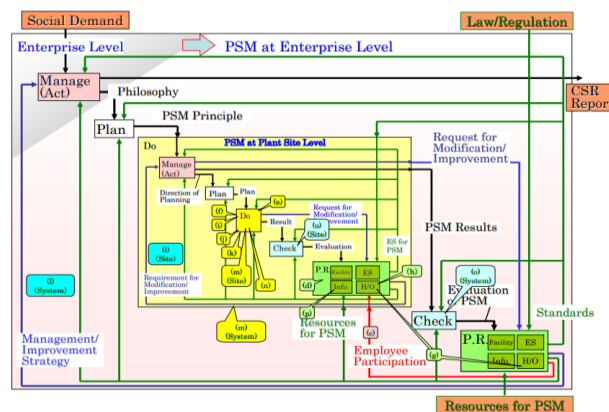


Fig. 1. Mapping of OSHA/PSM elements

PSM components can be successfully integrated into a PDCA (Plan Do Check Act) framework on an enterprise level as well as at the plant site. The plant-site tier is responsible for implementing processes such as process hazard analysis, pre-start-up safety review, mechanical integrity, hot work permits [9], incident investigation, and emergency preparedness, all under the direction of management. The two levels of the PDCA cycle, as well as compliance audits of performance at the plant and corporate levels, guarantee that the PSM system is continuously improved. Employee participation, training, and trade secrets are all seen as resources that help the organization remain prepared throughout the plant lifecycle.

2) Compliance-Driven Approaches

Process Safety Management (PSM) approaches based on compliance usually emphasize the goal of satisfying regulatory and statutory requirements and legal necessities set forth by the government or industry[10]. Such strategies focus on systematic records, obligatory protocols, and regular inspection to prove compliance with the recommended norms such as:

- **Regulatory Alignment:** Implementation of safety programs in accordance with national and international regulations (e.g., OSHA PSM, Seveso Directive), ensuring legal conformity.
- **Prescriptive Requirements:** Using established protocols and technical criteria to determine minimal safety standards for equipment design, operation, and maintenance.
- **Documentation and Recordkeeping:** Procedures, records of inspections, and audits that show compliance with current process safety information.
- **Periodic Auditing and Inspection:** Internal and External regular inspections to check that the regulatory requirements and safety standards.
- **Enforcement and Accountability:** Creation of roles, responsibilities and possible penalties to ensure safety regulations followed.

B. Elements of Process Safety Management (PSM)

The organization's successful PSM program leads to the development of operational discipline. Without a doubt, the PSM program boosts dependability, productivity, and quality while assisting the company in turning a profit [11]. This are type include shown in Figure 2.

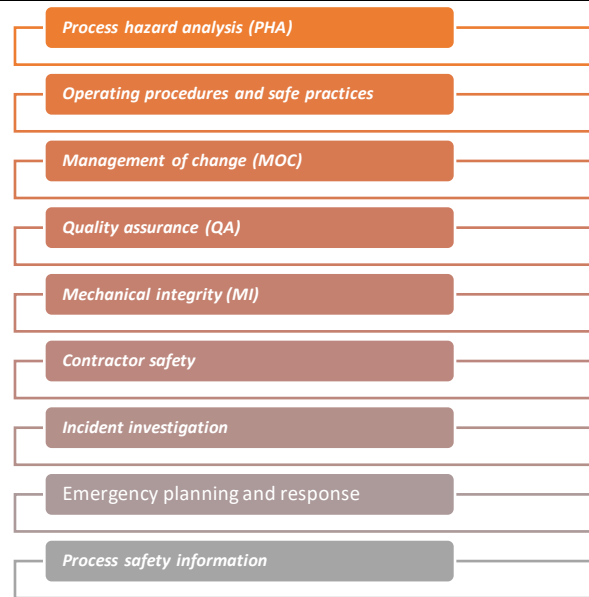


Fig. 2. Element of process safety management

1) *Process hazard analysis (PHA)*

A process hazard analysis is a method for systematically finding, assessing, and controlling risks associated with processes that use potentially dangerous substances. In both the planning and execution stages of a project, this type of study is necessary for potentially dangerous systems. Pre-Held Evaluation Conducted During the Game Various methodologies can be employed in the process, such as what-if analysis, HAZOP, fault tree analysis, failure modes and effects analysis, and others.

2) *Operating procedures and safe practices*

The employer is responsible for creating and enforcing documented operating procedures that outline the steps to take in order to carry out plant activities in a safe manner [12]. Every step of the process has to be carefully considered and tailored to the specifics of the plant's current setup. Workers need proper training to operate any machinery or systems in which they are involved.

3) *Management of change (MOC)*

Any modification to the process system, current equipment, etc., requires careful planning, evaluation, and approval. With MOC, the company may monitor and record any modifications to the current system, and those modifications are then made public.

4) *Quality assurance (QA)*

A key component of any new project's execution is quality assurance. Engineering standards are used to evaluate all system components, including parts, equipment, controls, and more [13]. The vendor's material test results, certificates of compliance, equipment test reports, and any other pertinent paperwork are examined before the item is accepted.

5) *Mechanical integrity (MI)*

The mechanical integrity module is an essential part of the operating phase of the system [14]. In accordance with the technical specifications, all system maintenance audits and monitoring must be carried out. Any process-critical equipment or control system that requires maintenance must also undergo such work in accordance with applicable technical standards and regulations.

6) *Contractor safety*

A lot of the time, contractors don't know about all the processes and risks in the plant. Emergency scenarios necessitate that contractors receive comprehensive orientation. Like homeowners, contractors might not know what kind of permits, inspections, etc. are needed before a task is started. They can also be unaware of the necessary criteria.

7) *Incident investigation*

A comprehensive investigation is required to identify the underlying causes of a safety incident that has been reported in the facility. It is imperative that this type of investigation be launched promptly following the incident in question, while the relevant employees are still cognisant of the facts.

8) *Emergency planning and response*

Accidents happen even with the best planning, so it's important that workers know what to do in an emergency through training and pre-planning. A comprehensive plant-wide emergency safety strategy is thus required.

9) *Process safety information*

A crucial component that gathers data on all potentially dangerous compounds is process safety information. System and equipment technical details are also contained in it [15]. The foundation for determining the information needed to conduct a comprehensive PHA is the collecting of process safety data. Various components of PSM, including as administrative controls, equipment, and people, are outlined below as safety barriers.

C. Functional Safety and Safety Integrity Frameworks

Functional safety structures are systemic specifications to ensure that safety-associated systems can execute the desired protective roles in the prescribed operating scenarios. These structures are especially important in hazardous industries where instrumented protection should be able to nullify or reduce disastrous situations with high reliability. Functional safety is a discipline that combines engineering design, verification, validation and lifecycle management in order to ensure levels of risk that are tolerable.

1) IEC 61508 and IEC 61511 Standards

Manufacturers and providers of equipment for safety instrumented systems are required to comply with the requirements of the IEC 61511 standard [16]. The primary categories of requirements outlined in the international standard IEC 61508 pertain to the hardware and the procedures for ensuring safety. standardization of electrical, electronic, and programmable electronic system functional safety; an overarching structure for such standard. It specifies the necessary conditions for safety-related systems throughout their lifetime, which includes hazard assessments.

2) Safety Integrity Levels (SIL)

The SIL is the relative or target degree of risk reduction for a safety function [17]. A safety instrument's dependability performance is defined by its Safety Integrity Levels (SIL), which are, in a nutshell, a measurement For example, according to Table I, SIL 1 offers a risk reduction factor (RRF) of 10-100 (PFDavg between 10⁻³ and 10⁻¹), while SIL 4 is the most stringent level of integrity, guaranteeing that safety instrumented systems reduce risks in direct proportion to the seriousness and frequency of detected dangers.

TABLE I. SAFETY INTEGRITY LEVELS (SIL) ACCORDING TO IEC 61508 / IEC 61511

SIL Level	PFDavg (Low Demand Mode) – Average Probability of Failure on Demand (per year)	Risk Reduction Factor (RRF)	PFH (High Demand / Continuous Mode) – Probability of Failure per Hour
SIL 4	≥ 10 ⁻⁵ and < 10 ⁻⁴	100,000 – 10,000	≥ 10 ⁻⁹ and < 10 ⁻⁸
SIL 3	≥ 10 ⁻⁴ and < 10 ⁻³	10,000 – 1,000	≥ 10 ⁻⁸ and < 10 ⁻⁷
SIL 2	≥ 10 ⁻³ and < 10 ⁻²	1,000 – 100	≥ 10 ⁻⁷ and < 10 ⁻⁶
SIL 1	≥ 10 ⁻² and < 10 ⁻¹	100 – 10	≥ 10 ⁻⁶ and < 10 ⁻⁵

3) Safety Instrumented System Governance

The governance of SIS needs to involve structured lifecycle management that comprises design verification, independent verification, periodic proof testing, and change management (MOC). Governance has the Safety Instrumented Systems be of a reliable nature during the entire time of operation and also address the targeted SIL requirements. Under PSM, functional safety systems.

III. PROCESS SAFETY IMPLICATIONS OF MECHANICAL SYSTEM DESIGN AND OPERATION

The effectiveness of process safety in industries with a high-risk profile is directly influenced by the way mechanical systems are designed and operated. Deterioration, containment loss, and catastrophic failures can be prevented by careful consideration of materials, safety margins, inspection, and maintenance. Mechanical integrity and risk assessment are integrated into lifecycle management to guarantee long-term safety and reliability in operations.

A. Mechanical Integrity and Reliability Engineering

Reliability engineering and mechanical integrity are key to the assurance of the safety-critical equipment functioning in accordance with its operational lifecycle[18]. These disciplines are addressed within Process Safety Management (PSM), which aims at preventing the loss of containment, reducing the probability of failures, and maintaining the performance of the assets by using systematic inspection, maintenance, and reliability analysis. Key elements include:

- **Asset Integrity Management:** Organized inspection, testing, and maintenance of pressure vessels, piping, and rotating equipment.
- **Failure Mechanism Identification:** Tests of corrosion, fatigue, creep, erosion, and other degradation tests.
- **Reliability-Centered Maintenance (RCM):** Risk-based maintenance schedules to optimize operational dependability and safety.
- **Performance Monitoring and Continuous Improvement:** Condition monitoring, failure data analysis, and audits should be used to improve long-term safety performance.

B. Hazard Identification and Risk Assessment in Mechanical Design

A systematic approach to assessing dangers and risks is given by the HIRA research [19]. The HIRA. When it comes to risk management, safety is a key factor in determining a hazard's function.

1) *Mechanical Hazards*

- **Moving machine parts:** The machine's rotating or reciprocating components may result in amputations, cuts, or crushing injuries.
- **Flying debris:** Loose materials or fragments might turn into projectiles during machine operation, endangering adjacent workers or operators.
- **Pinch points:** Pinch points, where two moving pieces meet, are a potential source of harm

2) *Electrical Hazards.*

- **Electric shock:** Electric shock is a potentially lethal risk for operators or maintenance workers in the event that the machine's electrical system has a malfunction.
- **Fire or explosion:** There is a danger of fire or explosion due to electrical problems that cause overheating or arcing.

3) *Chemical Hazards*

- **Exposure to hazardous substances:** Chemicals like solvents and cleaning agents may be used in some industrial processes [20], which may cause skin or respiratory irritation or have long-term health consequences
- **Pinch point hazard:** A serious injury could occur if the machine's moving components—like gears or rollers—caught a person's fingers or hands
- **Risk assessment:** There is a moderate to high risk of pinch point accidents, which can lead to the crushing or amputation of fingers. Prevention measures can be taken by putting in place emergency stop buttons, safety guards, and operator training.

4) *Mitigate the hazard*

The identified dangers and the risks they pose can be reduced through the implementation of various management measures.

5) *Engineering Controls*

- **Install machine guards:** Physical barriers, by blocking access to potentially dangerous moving parts, can lessen the likelihood of injuries.
- **Use interlocks and emergency stop buttons:** Installing machine interlocks is a good way to prevent machines from running when guards are open. Everyone should be able to quickly and readily reach the emergency stop buttons.
- **Implement proper ventilation:** Proper ventilation systems must be installed in locations where chemical exposure could occur in order to eliminate potentially harmful airborne vapors or particles.

6) *Administrative Controls*

- **Provide adequate training:** Machine operators and maintenance staff should undergo regular training to learn the machine's risks and how to operate it safely.
- **Develop and implement safe work procedures:** Operating safely, controlling hazards, and responding to emergencies all need to be outlined in well-defined and comprehensive work procedures.
- **Conduct regular maintenance and inspections:** The machine should undergo routine inspections and maintenance to find any problems or dangers and fix them right away.

7) *Personal Protective Equipment (PPE)*

Workers should be provided with the appropriate PPE, such as safety glasses, gloves, earplugs, and a respirator, based on the identified risky exposures.

8) *Safety Instrumented and Mechanical Protection System*

A safety instrumented and mechanical protection system, with its most essential functions and risk mitigation functions listed in Table II. Their relative role in the Process Safety Management integration of mechanical engineering practice.

TABLE II. COMPARISON AND INTEGRATION OF SAFETY INSTRUMENTED AND MECHANICAL PROTECTION SYSTEMS

Category	Safety Instrumented Systems (SIS)	Mechanical Protection Systems	Risk Reduction Mechanism	Lifecycle Consideration
Primary Objective	Detect hazardous deviations and automatically initiate corrective action	Prevent physical failure or loss of containment	Interrupt escalation of abnormal conditions	Incorporated during design and validated during commissioning
Operating Principle	Sensor → Logic Solver → Final Control Element	Self-actuating mechanical or passive response	Active intervention based on process variables	Designed according to pressure/structural codes
Typical Equipment	Sensors, PLCs, shutdown valves, ESD systems	Pressure relief valves, rupture discs, blast walls, containment systems	Provides an independent protection layer	Requires periodic mechanical integrity verification
Safety Integrity Requirement	Designed and verified to specified Safety Integrity Level (SIL)	Not typically SIL-rated; governed by mechanical design standards	Quantified risk reduction factor (RRF)	Periodic proof testing (SIS) vs. inspection and NDT (mechanical)
Dependency on External Power	Requires electrical/control power supply	Generally independent of electrical power	Ensures redundancy in protection layers	Consideration during reliability assessment
Failure Modes	Sensor drift, logic solver failure, valve sticking	Spring fatigue, corrosion, blockage, mechanical wear	Addressed through redundancy and inspection	Managed via Maintenance & Management of Change (MOC)

Role in PSM Framework	Instrumented safeguard within Layer of Protection Analysis (LOPA)	Mechanical Integrity (MI) element ensuring containment	Contributes to overall risk reduction strategy	Integrated into asset lifecycle management
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IV. INTEGRATION OF PROCESS SAFETY MANAGEMENT WITH MECHANICAL ENGINEERING PRACTICES

PSM combined with mechanical engineering practices allows integrating the principles of safety throughout the equipment lifecycle, including the design and installation stages, as well as the operation and maintenance stages[21]. Mechanical integrity programs, risk-based inspection, reliability centered maintenance. This integration makes the assets more reliable, proactive risk mitigation, and continuous improvement of the industrial safety performance.

A. Mechanical integrity and asset Reliability Management

The management of mechanical integrity and the management of asset reliability is to ensure that the safety-critical equipment discharges its intended duty throughout its lifecycle in a manner that does not cause any form of failure that may result in loss of containment or any risky occurrences[22]. These activity levels are risk-based and systematized levels in Process Safety Management.

Key components include:

- Inspection and Preventive Maintenance Programs:** Implementation of regular pressure vessel, piping, rotating equipment, and storage tanks inspection, testing, and preventive maintenance to identify the degradation mechanism including corrosion, fatigue, creep, and erosion prior to failure.
- Risk-Based Inspection (RBI) and Reliability-Centered Maintenance (RCM):** Implementation of risk evaluation techniques to determine and prioritize activities performed during maintenance in order of significance and probability of failure whereby high-risk equipment is accorded improved monitoring and additional resources.
- Performance Monitoring and Continuous Improvement:** Equipment dependability, downtime, and safety process performance can be improved by the use of condition monitoring techniques (thermography, vibration analysis, non-destructive testing), audit reviews, and analysis of failure data. Top of Form

B. Bottom of Form Process Safety Risk Categorization in Industrial Systems

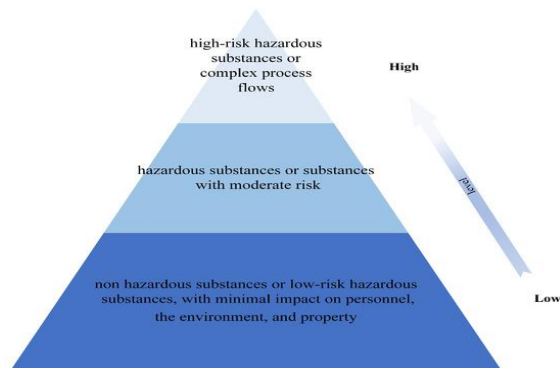


Fig. 3. The safety level of the process industry

The main components of process industrial systems include the following: hydrogen stations, liquefied natural gas, oil and gas generating firms, offshore drilling, cryogenic fuel loading systems, petrochemical, petroleum and chemical industries, operators, programmable systems and related equipment. A simple definition of a process control system would be a system that allows a process to react to signals sent in from outside sources. Figure 3 shows a typical classification system in action:

- Low risk level:** This category is suitable for low-risk, reasonably predictable industrial operations [23]. Little or no harm to humans, wildlife, or property may result from the use of low- or nonhazardous compounds in these operations. To meet the requirements for this level of safety, standard operating procedures and generic safety measures can be utilized.
- Moderate risk level:** This degree of danger is appropriate for production procedures that could severely damage people, ecosystems, and private property. These procedures may include the use of chemicals that are either very dangerous or moderately so. Strict security protocols and management systems are required to ensure effective risk control at this level.
- High risk level:** Industrial procedures that pose a substantial risk to persons, the environment, or property are subject to this level. These processes often include complex flow diagrams or the use of hazardous materials with a significant potential for harm. Strict management methods, security processes, and strategies are required to guarantee security at this level.

C. The framework of industrial accidents and the prevention mechanisms

A lifecycle-based Process Safety Management (PSM) integration framework that aligns technical, organizational, and regulatory components within a structured system[24]. The concept of lifecycle process safety is defined first, including standards, procedures, and international regulations. Then, technical failures, human factors, and equipment malfunctions are addressed through systematic hazard identification and risk analysis. Figure 4 shows how regulations are translated into operational actions.

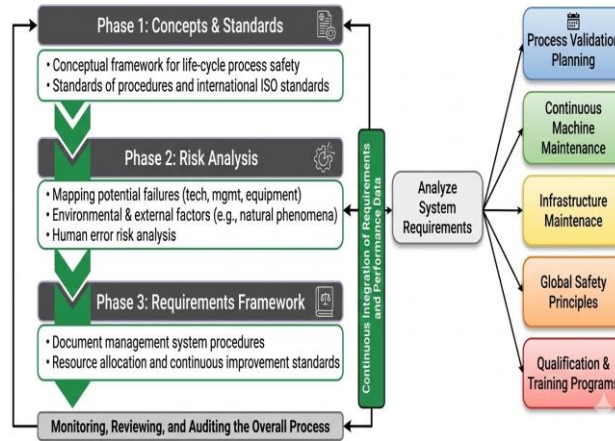


Fig. 4. Overall identifications for estimating the risk

such as validation planning, continuous maintenance of machinery and infrastructure. The framework emphasizes reviewing technical and social perspectives and concludes with continuous monitoring, auditing, and overall process evaluation, reflecting a structured and iterative safety management approach.

D. Lifecycle Monitoring, Management of Change, and Continuous Improvement

Lifecycle monitoring, MOC, and continuous improvement are essential components of integrating PSM with mechanical engineering practice. These components keep a mechanical system's safety performance up throughout its lifecycle, from design and commissioning to operation, modification, and decommissioning.

- **Lifecycle Monitoring:** Continuous assessment of equipment condition and operating parameters using inspections, condition monitoring, and integrity operating windows (IOWs) to prevent degradation and loss of containment.
- **Management of Change (MOC):** Risk assessment and mitigation through controlled testing of proposed changes to machinery, processes, or procedures.
- **Continuous Improvement:** Ongoing enhancement of safety performance through audits, incident investigations, root cause analysis, and incorporation of lessons learned into design and maintenance practices.

E. Process safety management principle in mechanical practice

A sector-wise integration of Process Safety Management (PSM) principles into mechanical engineering practice. It outlines key mechanical hazards, associated risk levels, relevant PSM elements, engineering control measures, and monitoring strategies across industries in Table III. The comparison emphasizes risk-based implementation, mechanical integrity, and continuous improvement to enhance safety and operational reliability.

TABLE III. INTEGRATION OF PROCESS SAFETY MANAGEMENT (PSM) PRINCIPLES INTO MECHANICAL ENGINEERING PRACTICE ACROSS INDUSTRIAL SECTORS

Industrial Sector	Mechanical System Hazards	Risk Level	PSM Integration Elements	Mechanical Engineering Controls	Monitoring & Continuous Improvement
Petrochemical & Refining	Pressure vessel rupture, piping corrosion, rotating equipment failure, overpressure, fire/explosion	Medium-High	PHA, MI, MOC	Risk-Based Inspection (RBI), corrosion monitoring, pressure relief system design, preventive & predictive maintenance	Online condition monitoring, vibration analysis, integrity audits, competency training
Wastewater Treatment Plants	Structural degradation, pump failure, gas accumulation (H ₂ S, CH ₄), confined space risks	Medium-High	Asset Integrity Management, Operating Procedures, Emergency Planning	Corrosion-resistant materials, redundancy in pumping systems, ventilation design, preventive maintenance	Gas detection systems, structural inspection programs, maintenance performance metrics
Chemical Manufacturing	Thermal runaway, reactor overpressure, mechanical seal failure, leakage of hazardous chemicals	Medium-High	PHA (HAZOP), Functional Safety, Mechanical Integrity, Incident Investigation	Safety Instrumented Systems (SIS), relief valve sizing, mechanical seal reliability programs	Performance testing of safeguards, reliability data analysis, periodic safety audits

Large-Scale Industrial Facilities	Fatigue failure, structural instability, impact loading, equipment misalignment	Medium-High	Integrity Operating Windows (IOWs), MI, Contractor Safety Management	Structural health monitoring, non-destructive testing (NDT), alignment and balancing programs	Lifecycle asset management review, failure trend analysis
Pharmaceutical Industry	Containment breach, contamination from equipment failure, HVAC system malfunction	Medium	Quality Risk Management, MI, Change Management	Cleanroom mechanical validation, HVAC preventive calibration	Environmental monitoring, deviation tracking, equipment qualification audits
General Industrial Operations	Machinery entanglement, hydraulic system failure, stored energy release	Medium	Safe Work Practices, Training, Mechanical Integrity	Guarding systems, lockout-tagout (LOTO), pressure isolation design	Compliance inspections, safety performance indicators

V. LITERATURE REVIEW

This section reviews prior research on process safety management in mechanical systems. Table IV provides a structured comparison of existing studies, highlighting key trends, challenges, and future directions.

Askari *et al.* (2026) studied process safety culture in combined cycle power plants using a fuzzy Full Consistency Method (FUCOM). A panel of ten process safety experts from the power generation sector. Cycle power plants can greatly improve their process safety performance and decrease the likelihood of major accidents by applying the fuzzy FUCOM approach to determine the relative importance and final weight of the most influential principles in a successful process safety culture. These principles include hazard and risk awareness with proactive response, resistance to normalization of deviations, and practical insights for safety manager frameworks that support targeted resource allocation [25]. A. Braniff *et al.* (2025) provided methods for managing process safety, such as fault diagnosis and prognosis and dynamic risk analysis. Integrating cyber-physical systems, conducting cyber-physical demonstrations, integrating operability and safety, and implementing safe data-driven control are all methods for advanced operability and control that are grounded in operations and process safety management. These methods seek to achieve operational excellence while proactively reducing potential safety losses. Ongoing innovations of the RETRO framework for safe and smart process operations are presented below, with an eye toward this end [26].

Wang, Zhou and Wang (2024) The prevention of serious accidents relies heavily on PSM. However, present PSM practices do not adequately bridge the gap between research and practice, which hinders the overall growth of PSM. In order to optimize PSM and enhance professional knowledge, PSM methodically incorporates many forms of evidence, such as incident reports, danger assessments, safety audits, and scientific publications. The first step is to analyze the development of PSMs, paying special attention to the problems with the safety data and operational procedures that were there. To demonstrate the generalizability of EBPSM, the framework is applied to the LNG marine safety management system [27].

Rashid *et al.* (2023) There is a lack of PSM in the literature. Any industry in any country, whether developing or developed, can start implementing PSM by following the general approach provided in this article. e, PSM forms development and other trainings. The case study uses ALOHA to estimate and quantify ammonia leakage. Industry utilizing PSM requires the development of nine different forms. PSM that adheres to recommended formats and procedures, which might aid engineers in comprehending PSM deployment [28]. Zhang *et al.* (2023) evaluated process industrial systems for safety and brought attention to the primary areas of investigation. The examination of information pertaining to process safety has led to the discovery of several mishaps that endanger human life and create health problems, as well as deterioration in health. Process industrial system safety evaluations and analyses have reviewed and summarised the methodologies and models' current research themes and development [29].

G. A, and S. Thomas (2022). A reliable safety management system is essential in light of the increasing frequency of incidents on construction sites. Few studies have examined the elements that contribute to risk management, and most private construction companies continue to use the time-honored methods that have been around for a long time. In addition, the study details the dangers of managing building projects, grades those dangers using the HIRA method, and suggests ways to deal with the most serious ones [30].

TABLE IV. COMPARATIVE ANALYSIS OF CHALLENGES AND FUTURE DIRECTIONS IN PROCESS SAFETY MANAGEMENT FOR MECHANICAL SYSTEMS

Author	Study On	Key Finding	Challenges	Future Work
Askari et al. (2026)	Process safety culture using fuzzy FUCOM	Hazard awareness ranked most critical cultural factor.	Limited expert sample; sector-specific focus.	Apply to other industries; integrate digital tools.
A. Braniff et al. (2025)	Dynamic risk analysis & RETRO framework	Real-time risk-based optimization improves safe operations.	Complex cyber-physical integration; implementation difficulty.	Large-scale validation; enhance safety-aware control.
Wang, Zhou & Wang (2024)	Evidence-Based PSM (EBPSM)	Integrating evidence improves PSM decision-making.	Poor safety data integration in traditional PSM.	Develop digital evidence systems; expand industry use.
Rashid et al. (2023)	PSM implementation procedure	Structured forms support practical PSM adoption.	Low awareness and training gaps.	Digitalize forms; develop training frameworks.
Zhang et al. (2023)	Safety analysis of process systems	Safety and reliability must be integrated.	Fragmented analytical methods.	Develop predictive and AI-based safety models.
G. A & S. Thomas (2022)	Construction risk management using HIRA	HIRA improves construction risk identification.	Lack of formal safety frameworks.	Create structured sector-specific SMS models.

VI. CONCLUSION AND FUTURE WORK

This study examines Process Safety Management (PSM) systems and their fundamental connection with mechanical systems in complicated industrial processes. The primary interface to the process industries in terms of containment and energy-handling is the mechanical equipment, and therefore the integrity of the equipment is critical in the engineering design, operational discipline, inspection of major accidents. The principles of mechanical integrity, risk assessment, and functional safety are a multilayered protection system that reduces losses of containment and failure of operations. Proactive decision-making and the preservation of safety barriers under changing operating environments by lifecycle-based combination of hazard identification, reliability engineering, and change management is used to sustain reliability, minimize uncertainty, and increase overall industrial safety maturity. Safety Instrumented Systems, mechanical protection layers, and risk-based maintenance strategies are used to enhance redundancy and resilience in industrial processes to adaptive, data-driven in nature, and performance-oriented PSM models.

Predictive analytics, AI, and real-time condition monitoring are digital tools that should be included in mechanical integrity programs in future work. The integration of reliability engineering, functional safety, and evidence-based decision-making into unified frameworks will further improve risk control. Also, studies on adaptive risk models, integration of cyber-physical systems, and the use of data-driven asset management strategies will enhance safer, smarter and more resilient industrial operations.

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