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Systematic Review

A Systematic Review of Asset Integrity and Process Safety Management Sustainability for Onshore Petrochemical Installations

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Abstract: This paper presents a systematic review of the contributions of asset integrity and process safety management for the safe operations and sustainability of onshore petrochemical installations. The review highlights how the two systems work as prerequisites for minimizing industrial accidents and preserving the environment. Their contributions to the management of safety-critical equipment and the integration of the emerging technologies of Industry 4.0 are provided. Based on a systematic review of more than one hundred academic papers and gray literature, the authors highlight considerable gaps associated with the operations of the two systems mostly functioning without integration. The authors propose a new conceptual framework, integrated asset integrity and process safety management (iAIPSM), to address the gaps. This review provides insights to strengthen operational safety, ensure regulatory compliance, and support the advancement of the United Nations Sustainable Development Goals (SDGs) within the sector.

Keywords: asset integrity; process safety sustainability; onshore petrochemical installations; integrated asset integrity and process safety management systems

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1. Introduction

The oil and gas industry, one of the most important cornerstones of the global economy, is profoundly anchored in onshore petrochemical installations. These infrastructures are pivotal in transforming crude oil and natural gas into a spectrum of high-value products such as gasoline, diesel, and petrochemicals. Despite their economic significance, these installations operate in an environment fraught with inherent risks. The complexities in processing highly flammable and hazardous materials make safety and asset integrity management paramount. Reported incidents at these facilities often stem from equipment failures, posing grave threats to human life, the environment, and economic stability [1]. The repercussions include fatalities, serious injuries, operational downtimes, extensive repair costs, legal liabilities, and irreversible damage to reputations [2]. In these settings, asset integrity management (AIM) and process safety management (PSM) emerge as important disciplines to proactively identify and mitigate risks associated with processes handling highly hazardous materials. PSM is a multifaceted approach that integrates preventive and corrective measures along with robust safety protocols and procedures [3]. AIM compliments PSM by focusing on the reliability and integrity of physical assets. This includes equipment maintenance and the upkeep of infrastructure and operational processes for safe operations [4–8].

Historically, AIM and PSM have been treated as separate disciplines, managed independently with ad hoc interfaces. However, there are synergistic benefits of integrating the two systems to bring about a paradigm shift in the industry to leverage the strengths of both systems. This can foster a comprehensive approach to achieving their common goal of reducing risks to levels as low as reasonably practical (ALARP), presented by Figure 1, where potential hazards are reduced to the lowest possible levels, with the costs, efforts, and strategies involved being significantly outweighed by the resulting benefits. The novelty of this holistic review firstly lies in the identified gaps associated with the non-integratedness of the concepts of AIM and PSM. The research, furthermore, through an exploratory review process, demonstrates the gains associated with the integration of AIM and PSM over the isolated deployment of these concepts. Furthermore, an innovative, unified framework that integrates AIM and PSM, designed to bridge identified gaps, is proposed. Furthermore, practical and actionable recommendations for industry practitioners, policymakers, and regulatory agencies are presented.

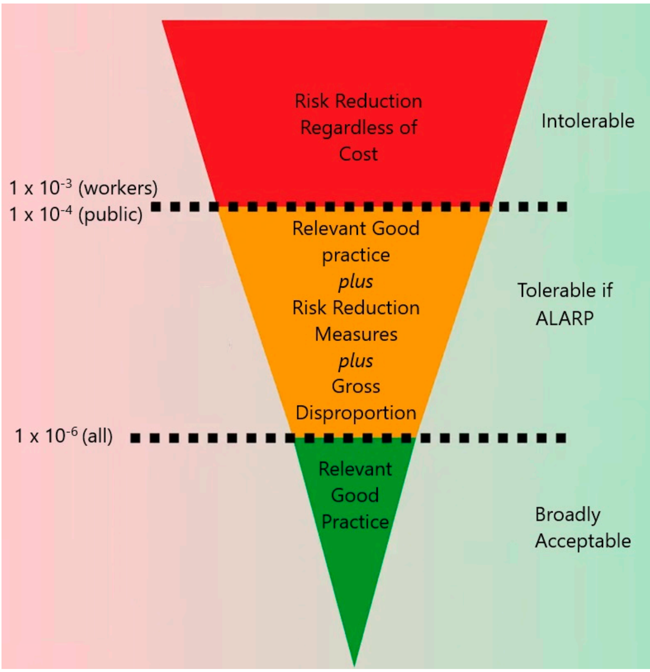

Figure 1. COMAH ALARP criteria: deaths per annum [8].

Recent technological advancements have the potential to catalyze this integration, for example, digital twins and predictive analytics that can allow for timely interventions to significantly improve asset reliability and safety [9–11]. A quintessential area where these new advancements can play a significant role is in the management of safety-critical equipment and systems (SCESs), also known as safety barriers. These include equipment whose failure can lead to catastrophic events, such as emergency shutdown, fire and gas detection, and pressure protection equipment [12,13]. Further synergies between AIM and PSM are evidenced by their combined contributions to an inherent safe design, which are instrumental in minimizing risks at their sources [14].

This research has addressed the following underlisted objectives and focus areas:

i. Identify the gaps in current industry practices and the literature by analyzing the existing industry practices and academic literature.
ii. Investigate the synergistic benefits of integrating AIM and PSM by analyzing the potential advantages of their combined implementation and their impact on advancing the effected SDGs.

iii. Propose an innovative, unified framework that integrates AIM and PSM, designed to bridge identified gaps.
iv. Provide practical and actionable recommendations for industry practitioners, policymakers, and regulators to effectively implement the proposed framework.

Rationale

The continued recurrence of major incidents within the industry is strongly tied to the fragmented implementation of AIM and PSM systems. Figure 2 shows the number of fatalities reported by the International Association of Oil & Gas Producers (IOGP) from 2014 to 2013. These incidents have led to the tragic loss of lives, irreversible environmental damage, and significant financial setbacks, posing challenges to meeting multiple UN Sustainable Development Goals (SDGs).

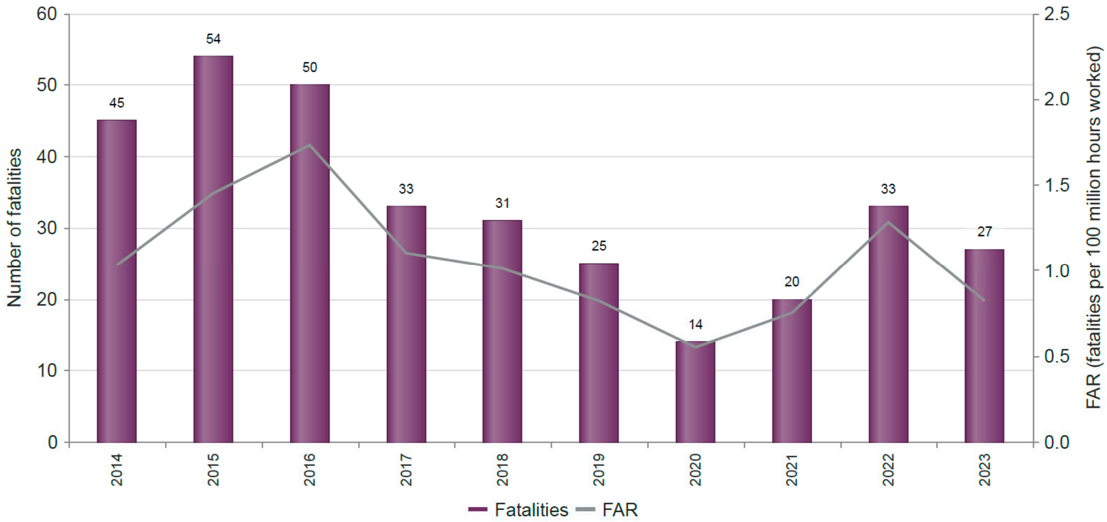

Figure 2. Number of industrial fatalities and fatal accident rate (2014–2023) [15].

The integration of AIM and PSM offers a transformative pathway towards advancing SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land). Table 1 provides a summary of nineteen major industrial incidents, depicting a set of case study scenarios, along with an analysis of their root causes directly linked to the mentioned SDGs.

Table 1. Major process safety incidents with fatalities [16].

Date	Country	Event	PSE Type	Fatalities	Reported Root Causes	Affected SDG
4 January 1966	France	Feyzin	BLEVE	18	Inadequate procedures	3, 6, 9, 12
23 July 1984	USA	Romeoville	Explosion	17	Inadequate inspection and testing	3, 6, 9, 12
2 December 1984	India	Bhopal	Chemical leak	>20,000	Poor process safety management Aging plants Poor emergency preparedness	3, 6, 9, 12, 13

Table 1. *Cont.*

Date	Country	Event	PSE Type	Fatalities	Reported Root Causes	Affected SDG
6 July 1988	UK	Piper Alpha	Explosion	167	Poor work practices	3, 8, 9, 12, 14
22 March 1987	UK	Grangemouth	Explosion	1	Safety instrumented systems failure	3, 6, 9, 12
9 November 1992	France	La Mède	Explosion	6	Poor plant layout	3, 9, 11, 12
21 January 1997	USA	Avon	Runaway reactions	1	Safety instrumented systems failure	3, 8, 9
23 February 1999	USA	Avon	Fire	4	Poor work practices	3, 8, 9
21 September 2001	France	Toulouse	Explosion	30	Inadequate process knowledge Poor hazard identification	3, 9, 12
23 March 2005	USA	Texas City	Explosion	15	Poor corporate safety culture Inadequate operating procedures	3, 6, 8, 9
27 July 2005	India	Mumbai High North	Explosion	22	Poor corporate safety culture	3, 6, 8, 9
5 November 2005	USA	Delaware City	Asphyxiation	2	Poor work practices	3, 8, 9
2 April 2010	USA	Anacortes	Explosion	7	Poor material selection during construction	3, 9, 12
20 April 2010	USA	Macondo	Explosion	11	Lack of training Inadequate process knowledge Poor hazard identification	3, 8, 9
19 November 2013	Belgium	Antwerp	Explosion	2	Inadequate equipment design	3, 8, 12
11 February 2015	Brazil	Camarupim	Explosion	9	Poor management of change process	8, 9
12 August 2015	China	Tiajin	Explosion	173	Failures of risk management systems	3, 9, 13, 15
22 March 2018	Czech Republic	Kralupy	Explosion	6	Human error Lack of supervision	8, 9
4August 2020	Lebanon	Beirut Port	Explosion	204	Lack of risk awareness Poor process safety management	3, 9, 12, 15

The 2017 Baker Panel Report [17], officially titled "*The BP U.S. Refineries Independent Safety Review Panel*", was initiated following the catastrophic Texas City refinery explosion in 2005. The panel sought to comprehensively assess BP Texas's AIM and PSM performance and provide actionable recommendations for improvement. Using quantitative analyses, the report examined key areas such as incident rates, employee perceptions, resource allocation, and compliance with safety practices, highlighting misaligned priorities that came with the management of AIM and PSM in isolation.

Table 2 provides the quantitative outcomes from the Baker Panel Report that are critical for understanding the root causes of safety challenges and guiding future safety improvements.

Table 2. The Baker Panel's main quantitative outcomes [17].

Research Area	Outcome/Metric	Description
Incident Rates	Higher rates of significant incidents at BP refineries compared to industry averages	Quantitative data highlighted a higher frequency of process safety incidents, demonstrating a need for improved controls.
Process Safety Metrics	Inadequate tracking and benchmarking of leading and lagging indicators (Tier 1–4 PSE)	Identified gaps in the systematic collection and analysis of key safety performance indicators.
Employee Safety Culture Surveys	40% of employees expressed concerns about management's commitment to safety	Quantitative survey results reflected skepticism about leadership's prioritization of safety initiatives.
Training Completion Rates	Less than 70% of employees received required process safety training	Indicated a significant gap in meeting process safety training requirements across facilities.
Resource Allocation	15% lower investment in safety infrastructure compared to industry benchmarks	Revealed insufficient financial resources allocated toward safety improvements relative to comparable facilities.
Incident Reporting Frequency	Fear of retaliation reported by 30% of survey respondents	Quantitative data from surveys showed reluctance among employees to report safety concerns due to fear of consequences.
Inspection and Maintenance	Delayed or incomplete maintenance in 25% of critical equipment reviews	Analysis of records showed consistent delays in adhering to inspection and maintenance schedules.

By providing quantitative evidence of deficiencies, the Baker Panel Report established a foundation for BP and the wider refining industry to adopt data-driven safety improvements.

In his book, ref. [18] presented a case study titled "a trip will fail to operate". Despite PSM being in place, a trip still failed to function adequately under certain stochastic conditions. The scenario described in the book presented a case scenario in which a trip valve, intended to close and open a valve when a temperature, pressure level, or concentration got too low or too high, failed to operate. As a result of this failure, tanks were seen overflowing, equipment got extremely hot, and other unwanted systems reactions played out due to the trip failure. It was noted that the various trip failures were due to reasons that spanned across the nonregular testing of trips, poor or non-thorough testing processes, altered testing set points, and a trip temporarily made inoperative for safety reasons, amongst others. However, it was pointed out that even though the above testing issues were the orchestrators of the trip failure, a special scenario referred to as "random failure" played out in another tripping event without testing issues, hence negatively impacting on the functionality of the tripping mechanism responsible for the control of a system of machines despite having no issues with testing. Random failure surpasses PSM but can be checked and largely minimized with the integration of AIM, which seeks to look beyond the traditional process safety management scheme. AIM focuses on reliability and availability, including the risk of operating a system under odd conditions for a sustainable period of time, hence fostering system adaptability to extreme scenarios.

In a similar scenario of tripping failure, out of 525 trials with testing, in 401 trials issues were detected prior to a failure regarded as dangerous, while in 0 trials were issues detected without testing. On the other hand, 69 dangerous failures were undetected with testing, while 470 dangerous failures were undetected without testing, and in 55 trials a safe failure was undetected without testing, and in 55 safe failure was undetected when testing was conducted. This resulted in an 85% diagnostic coverage of dangerous failures when testing was effected and a 0% diagnostic coverage of dangerous failures without testing

(Aschenbrenner, 2016). Despite conducting testing on the trip device, indicating PSM being in place, the level of failure could be seen to fluctuate in possible random scenarios beyond basic adherence to process safety management. Asset integrity management with a broad spectrum of enhancement strategies including re-design, design enhancement, and reliability-centric operations and control would minimize the level of exposure to failure of the tripping and control device.

Ref. [19] further presented a case study titled “a Heavy Oil Tank will foam over”. This case study depicts a case of AIM. An instance of foam-over was presented when a random staff member added hot oil at a temperature of over 100 degrees to a heavy oil tank containing a layer of water. The water vaporized with explosive violence. The height of the tank in this instance was 25 m. Apart from the tank rupturing, it was covered with black oil. To prevent this scenario from happening, the oil should have been cooled below 100 degrees, while a high temperature alarm should also have been fitted to the oil line. Otherwise, if this preventive measure would not have been possible, the liquid in the tank should have been kept above 100 degrees so that the water which got into the tank was vaporized. This follows from the fact that the oil at this point was highly viscous.

2. Materials and Methods

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (see Supplementary Materials). The process began with the definition of the research questions as advocated by [20,21]. Articles were sourced from academic and industry databases, including Google Scholar, Scopus, Semantic Scholar, and CrossRef. Gray literature was sourced from the internet webpages of oil and gas operators, the International Association of Oil & Gas Producers (IOGP), the Centre for Chemical Process Safety (CCPS), the US Occupational Safety and Health Administration (OSHA), the Energy Institute (EI), Shell AIPSM, the UK HSE Executive, British Petroleum SEMS, and the ISO 55001 standard series.

Searches were designed to be inclusive by using sing keywords and Boolean operators like “Process Safety Management AND Asset Integrity Management”, “Integration of PSM and AIM AND petrochemical installations”, and “safety-critical equipment AND Industry 4.0”. No temporal restrictions were applied, allowing for the inclusion of both foundational and contemporary studies. Harzing’s Publish or Perish tool facilitated efficient searches across these databases.

Included were published studies explicitly addressing PSM and AIM or their integration within the petrochemical sector that were published in peer-reviewed journals and industry reports. Studies outside the petrochemical context, lacking methodological rigor, or not in English were excluded. Studies that did not directly address AIM and PSM were also excluded following the screening process described by [21].

This systematic process identified 660 publications initially. After removing duplicates, 396 studies were retained for abstract screening. From these, 214 studies were found to align with the research objectives and were shortlisted. Full-text assessments further narrowed the selection to 164 articles for final analysis. Figure 3 presents the details of this screening and selection process.

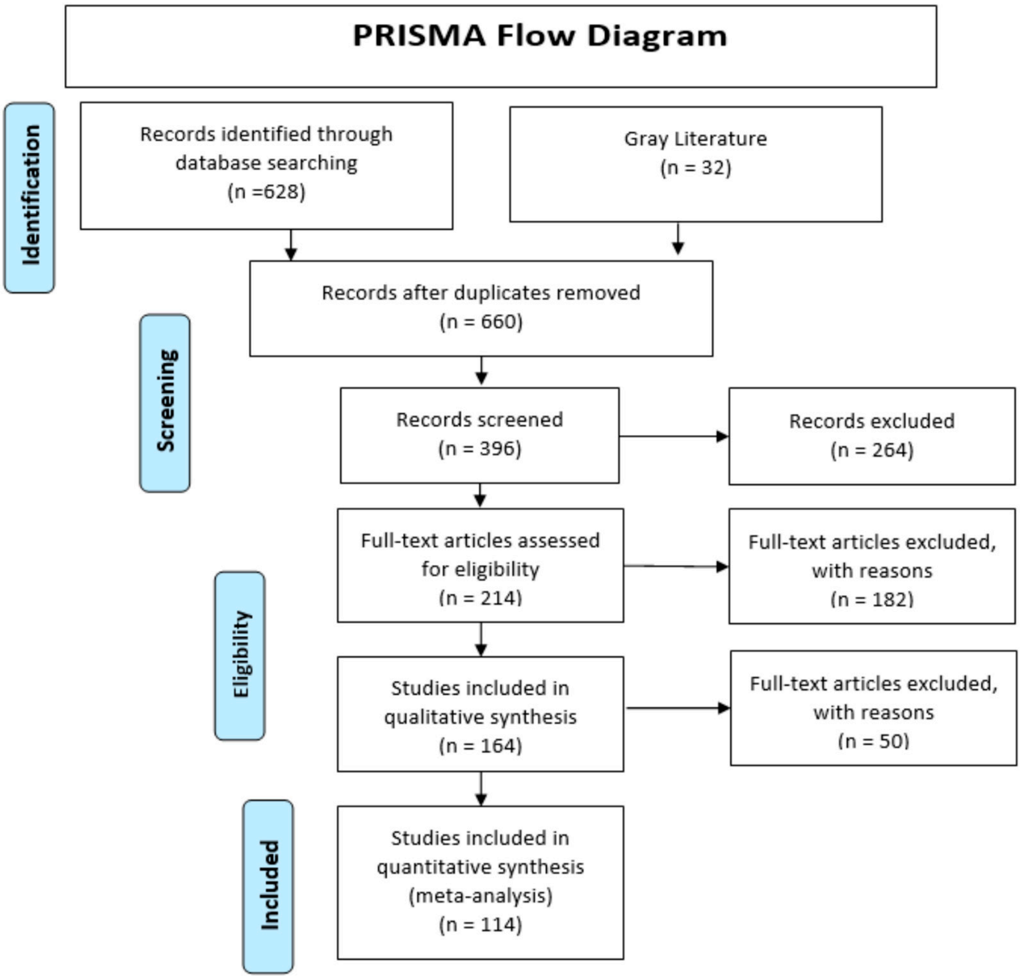

Figure 3. PRISMA workflow and results from article selection [22].

3. Results

A total of 114 peer-reviewed articles, including gray literature and publications, were considered. The analysis and interpretation of the articles and publications identified emerging technologies, risk reduction, and operational resilience as the main themes and contrasting viewpoints within the literature. The findings from the reviewed articles are reported in the Section 4 discussion.

4. Discussion

This section details the common AIM and PSM models and their contributions to the safety performance and sustainability of onshore refineries and petrochemical installations. The promises they bring with their integration with the emerging technologies of the fourth industrial revolution (4IR) are explored. Lastly, the systems' deficiencies and areas of improvement are summarized.

4.1. AIM and PSM Systems in the Industry

Table 3 lists the common PSM and AIM standards in the industry and the literature. Due to its broad focus, ISO 55001 [23] is the standard AIM reference in the industry. Other support systems that complement ISO 55001 include (i) Total Productive Maintenance (TPM), which aims to maximize equipment effectiveness through employee involvement and a focus on proactive and preventive maintenance [24]; (ii) reliability-centered maintenance (RCM), which focuses on prioritizing maintenance efforts based on the criticality of asset failures [25]; (iii) Lean Maintenance (LM), which applies sustainable principles to maintenance activities to reduce waste and improve efficiency [26]; and (iv) Six Sigma to reduce variability in maintenance processes and improve the overall equipment effectiveness [27].

Table 3. Common AIM and PSM standards with elements.

	Elements	OSHA	RBPSM	DuPont	EI PSM	Shell	UK-HSE	BP	ISO 55001
1	Leadership Commitment and Responsibility		√		√	√	√	√	√
2	Compliance with Legislation and Industry Standards		√		√	√	√		√
3	Employee Selection, Placement, and Competencies		√		√	√	√		
4	Workforce Involvement	√	√		√	√	√	√	
5	Communication with Stakeholders		√		√	√	√		
6	Document, Records, and Knowledge Management	√	√	√	√	√	√	√	√
7	Hazard Identification and Risk Assessment	√	√	√	√	√	√	√	√
8	Operating Manuals and Procedures	√	√	√	√	√	√	√	
9	Work Control, PTW, and Task Management	√	√	√	√	√	√		
10	Inspection and Maintenance	√	√	√	√	√	√	√	√
11	Contractor and Supplier Selection and Management	√	√	√	√	√	√	√	√
12	Training	√	√	√		√	√	√	√
13	Management of Change and Project Management	√	√	√	√	√		√	√
14	Operation Readiness and Process Startup	√	√	√	√	√		√	
15	Standards and Practices		√		√	√		√	√
16	Emergency Preparedness	√	√	√	√	√	√	√	
17	Incident Reporting and Investigation	√	√	√	√	√	√	√	
18	Process and Operation Status Monitoring and Handover		√		√	√	√	√	√
19	Audit Assurance and Management Review and Intervention	√	√	√	√	√	√	√	√
20	Management Review and Continuous Improvement		√			√			√
21	Trade Secrets	√							
22	Management of Subtle/Personnel Change			√					
23	Management of Safety-Critical Devices			√	√				√
24	Management of Operational Interfaces				√				
25	Support (Resources, Support Tools)	√							√

Table 3. *Cont.*

	Elements	OSHA	RBPSM	DuPont	EI PSM	Shell	UK-HSE	BP	ISO 55001
26	Planning (Risk Mitigation)								√
27	Asset Life Extension								√
28	Lifecycle Management								√

For clarity and to streamline resource allocation, the elements were organized into the focus areas of leadership, hazard identification, risk management, continuous improvement, and management reviews. This fostered a balanced approach to effectively integrate managerial, technical, and operational aspects. Table 4 outlines how these elements were grouped into their respective categories.

Figure 4 presents the CCPS Risk-Based Process Safety (RBPS) PSM system model, which is built on the categorization of the above elements into four main pillars: Leadership Commitment, Hazard Identification, Risk Management, and Continuous Improvement. This model provides a structured framework for integrating these critical elements into a cohesive safety management system.

Table 4. AIM and PSM elements grouped into their respective pillars.

Main Pillar	AIM/PSM Elements	Standards Addressed
Leadership Commitment	1. Leadership commitment and accountability 2. Workforce involvement 3. Stakeholder communication 4. Employee selection, placement, and competencies 5. Training and competencies 6. Open communication culture	OSHA PSM, RBPSM (AIChE), DuPont PSM, EI PSM, Shell PSM, UK HSE, BP SEMS, ISO 5500
Hazard Identification	1. Hazard identification and risk assessment 2. Process safety information 3. Incident reporting and investigation 4. Compliance with legislation and industry standards	OSHA PSM, RBPSM, DuPont PSM, EI PSM, UK HSE, Shell PSM, BP SEMS
Risk Management	1. Management of change (MOC) 2. Emergency preparedness and response 3. Asset inspection and maintenance 4. Safety-critical equipment and systems management 5. Operating procedures 6. Technical integrity 7. Contractor and supplier management	OSHA PSM, DuPont PSM, EI PSM, Shell PSM, UK HSE, BP SEMS, ISO 55001
Continuous Improvement	1. Audits and assurance 2. Management reviews 3. Data management and analytics 4. Lifecycle management 5. Operational readiness and learning systems 6. Process safety metrics 7. Performance monitoring 8. Continuous learning initiatives	RBPSM, Shell PSM, BP SEMS, ISO 55001, OSHA PSM, EI PSM

Table 4. *Cont.*

Main Pillar	AIM/PSM Elements	Standards Addressed
Management Reviews	1. Audit assurance and management reviews 2. Monitoring process and operational changes 3. Corrective action implementation	OSHA PSM, RBPSM, EI PSM, UK HSE, Shell PSM, BP SEMS

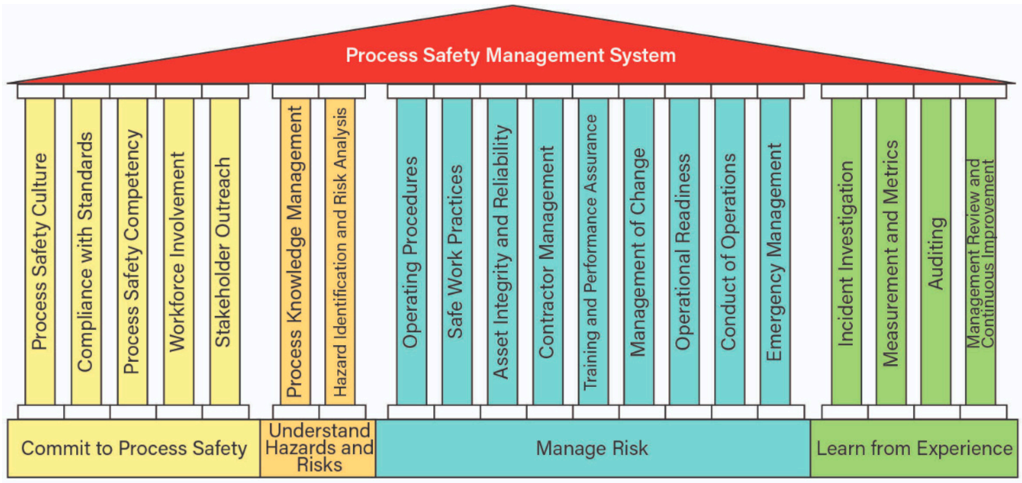

Figure 4. AIM/PSM element categorization into focus pillars [28].

4.2. AIM and PSM Contributions

While AIM and PSM systems may not directly be linked to the United Nations Sustainable Development Goals (SDGs), their contributions are significant and multifaceted. These systems embody the principles of safe, responsible, and sustainable industrial practices aligning with several SDG objectives [29], including SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

Fourth industrial revolution innovations and AI offer new opportunities for sustainability and open innovation. For instance, blockchain technology can enhance transparency and traceability in supply chains, as demonstrated in the Thai fish industry. Similarly, machine learning applications in pipeline integrity management showcase advanced proactive approaches that support environmental protection and sustainability goals [30,31].

4.2.1. Mitigation of Water and Air Pollution

Leaks and fugitive emissions from poorly managed equipment contributing to land, air, and water pollution contributing to climate change and posing risks to ecosystems and biodiversity directly touch on SDG 3, SDG 6, SDG 12, SDG 13, SDG 14, and SDG 15 [32]. The consequences can extend beyond the immediate vicinity of the installations, affecting larger regions at a global level. A study by [33] provided compelling evidence of the significant environmental and health risks posed by volatile organic compounds (VOCs) to communities located within the vicinity of an industrial facility. Accumulated VoCs with the fingerprints of the plant were found over large areas beyond the industrial park. The research emphasized the serious health risks associated with exposure to volatile organic compounds (VOCs), including respiratory issues, neurological disorders, and the potential for long-term cancer development. Additionally, it highlighted the environmental impact, particularly the decline in air quality and the resulting widespread ecological harm.

AIM and PSM systems can contain VoC releases by identifying and controlling their sources through monitoring protocols and maintenance practices.

The findings of [34] on VOC emissions from petrochemical industries within New Delhi, India, mirror those of [33]. The study recommended the implementation of advanced control technologies and asset integrity management to capture VOCs in a timely manner at their potential sources.

Other studies accentuating the importance of AIM and PSM systems in addressing water and air pollution include [35], which explored the environmental impact of particulate matter emissions from onshore refineries, and [36], which analyzed the broader effects of governing policies on environmental pollution. However, neither study addressed the critical role of human factors in the successful implementation of these systems.

4.2.2. Reduction in Process Safety Incidents

AIM and PSM are frameworks within the broader discipline of safety with pivotal roles in reducing industrial accidents, with their respective programs complementing each other. These include risk-based approaches with advanced decision-making capabilities to quantify risks and cost–benefit analysis [37–39]. However, ref. [40] argues that the successful implementation of these initiatives depends on fostering a strong safety climate through effective communication and encouraging employee participation.

4.2.3. Safeguarding Reputation

Public trust erodes with industrial incidents, especially when these contribute to safety and environmental conflicts with local communities. These can have detrimental effects on plants' reputations and undermine social licenses to operate. A study conducted by [41] on reputational risks in the oil and gas industry examined the role of social and mainstream media in influencing public opinions and perceptions. To avoid negative reactions from the public, industries must learn from their peers' past incidents to enhance their own accountability to build trust among consumers, investors, and regulatory bodies [42]. These observations are strongly supported by the research work presented in [43]. Here, the study focused on the public's perception of risks from the Carburos Metálicos petrochemical complex following several chemical-related accidents that resulted in fatalities between 2019 and 2020. The study used a public participation geographic information system (PPGIS) that correlated risk perception data from sociodemographic surveys to analyze the perceived risks from the public's perspective. The findings showed that the surrounding populations could identify the main sources of chemical risk and locations vulnerable to potential explosions. These results underscore the necessity of incorporating public perception into strategies aimed at improving Health, Safety, and Environmental (HSE) performance, emphasizing the crucial role of public participation in enhancing the safety and resilience of industrial operations.

4.2.4. Driving Industry 4.0 Advancements

The fourth industrial revolution (4IR) represents a transformative shift in industrial practices, characterized by an unprecedented fusion of technologies blurring the lines between the physical, digital, and biological spheres. Inputs from AIM and PSM systems are contributing to the advancement of 4IR technologies. For instance, inputs from an asset management system in Nigeria improved the performance of a 4IR technology algorithm under development whose outputs significantly altered road transport asset management practices [44]. Contributing to the advancing 4IR presents both opportunities and challenges; for example, efforts to digitalize process systems in one drilling establishment brought about heightened concerns about cybersecurity and the compromised reliability of automated systems and brought new challenges that required personnel to acquire new skill sets [45]. Therefore, the challenge for industries is to embrace the benefits of the

4IR while simultaneously developing robust strategies to mitigate the emerging risks and ensure the safety and integrity of their processes and assets.

AIM and PSM systems have enormous potential to expand the technological space of the fourth industrial revolution (4IR). The 4IR is the fusion of the physical and digital worlds and the utilization of AI, three-dimensional (3D) printing, and the Internet of Things (IoT) to create unprecedented opportunities in the industry [46]. The IoT is a network of physical items equipped with sensors, software, and other technologies linked together via the internet or other forms of communication. These devices are capable of data collection, coupled with securely sharing information without the need for a computer or human–computer interaction. In this context, IoT opportunities include the possibility for process control and safety equipment to communicate and share real-time information with each other. AI can analyze the historical data they generate to uncover patterns that can assist us to make predictions. To supplement AI, virtual models, which are the computational representation of real or abstract systems, can be created to simulate credible equipment and process scenarios [47]. Through simulations, they can envision complex processes and equipment failure modes for early interventions. These predictions assist us to make advance decisions to avoid or mitigate undesired conditions. Three-dimensional printing technologies can manufacture equipment and needed spare parts in-house on time and on demand, saving on delivery times and outsourcing costs.

Both systems generate substantial data that require analysis to produce usable management dashboards and key performance indicators (KPIs) for decision-making and continuous improvement. PSM KPIs include Four-Tiered Process Safety Events (PSEs) described in Figure 5, with Tier 1 incidents having severe financial losses, injuries, or fatalities. AIM KPIs include a focus on asset performance and availability [48–50].

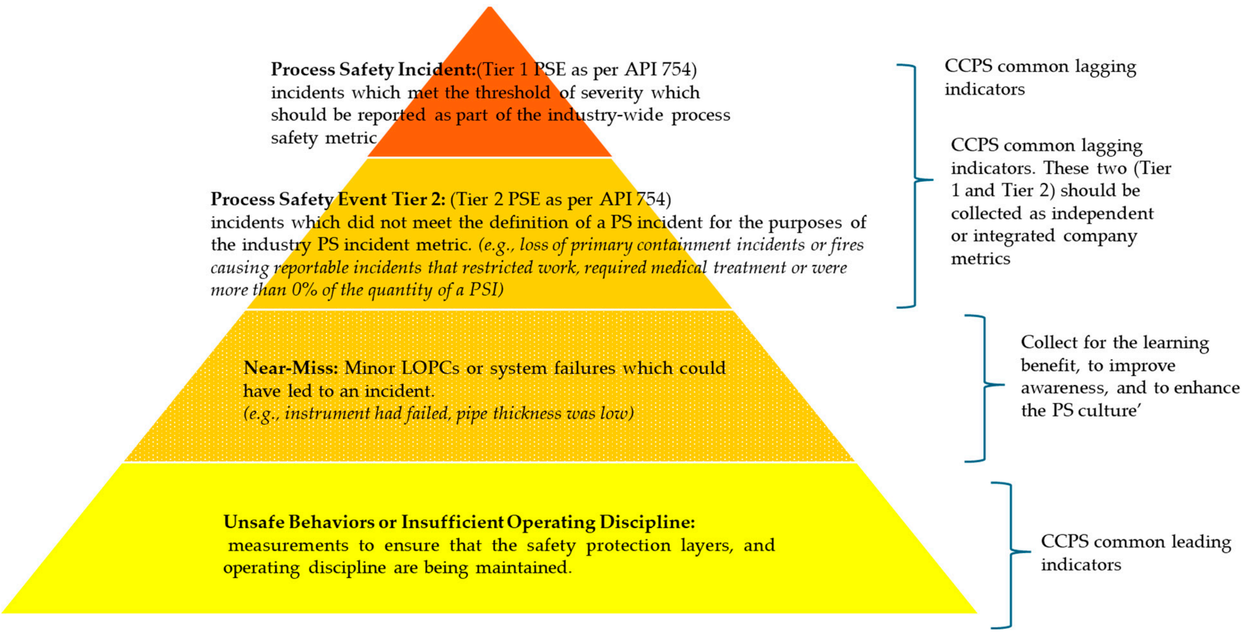

Figure 5. Process safety metric pyramid [51].

The practice of manually collecting and manipulating substantial amounts of background data through conventional methods such as Excel spreadsheets is time-consuming, prone to error, and often results in incorrect conclusions. Fourth industrial revolution technologies have the potential to automate most KPIs to improve operational efficiencies. KPIs can be integrated with virtual and augmented reality technologies to simulate credible scenarios to improve emergency response training programs [52–54].

4.3. Identified Gaps

This review identified seven gaps and opportunities to fuel further research. These are (1) the integration of AIM and PSM; (2) the establishment of regulatory frameworks to govern AIM and PSM; (3) the enhancement of human aspects, competencies, and organizational safety culture; (4) the incorporation of technological advancements; (5) the development of practical implementation guidelines for AIM and PSM; (6) a lack of continuous improvement through learning from experiences; and (7) a lack of comprehensive data analytics and management.

4.3.1. Integration Between AIM and PSM Systems

The discourse on the integration of AIM and PSM within the academic and professional literature remains sparse. This gap is evident in current industrial practices despite fundamental links between the two. Most studies examine AIM and PSM as separate domains, overlooking the interconnected relationship between physical asset integrity and chemical process safety. This prompted [55] to highlight the need for a cohesive approach, but they stopped short of providing an integration framework. These oversights underscore missed opportunities for enhancing operational safety and reliability through unified strategies that bridge the gaps between chemical process safety and the physical condition of assets.

4.3.2. Formulation of Comprehensive Regulatory Frameworks

This is a concern due to the amplified risks that come with the growing complexity of industrial operations. While there is a wealth of literature on the principles and practices of AIM and PSM, studies into the effectiveness of regulatory frameworks and enforcement mechanisms are sparse. Ref. [55] touched on the integration of safety and security in the chemical industry, acknowledging the role of regulations; however, the work did not delve into the specifics of how regulatory frameworks or their enforcement could impact AIM and PSM practices.

4.3.3. Human Factors, Employee Competencies, and Organizational Safety Culture

Human factors, encompassing a range of psychological, physical, and social interactions between humans and systems, significantly influence the effectiveness of safety management practices. When aligned with employee competencies (specific knowledge, skills, and abilities required to perform tasks safely and effectively), these elements can collectively contribute to a robust safety culture within an organization.

Human Factors

The current body of literature on AIM and PSM exhibits significant gaps in the areas of human factors, employee competencies, and organizational safety culture, presenting missed opportunities for advancing the understanding and implementation of safety management practices that are critical to preventing accidents and ensuring safe operations. Despite the acknowledgment of human errors as primary contributors to industrial accidents, there is a discernible lack of focused research that integrates human factors within the frameworks. For example, ref. [56] introduced a new accident model emphasizing complex socio-technical systems, highlighting the importance of considering human factors in safety management. However, detailed exploration into how human factors specifically influence the effectiveness of AIM and PSM strategies, including aspects such as human error, operator decision-making, and ergonomic design, remain sparse.

A study by [57] analyzed the systemic causes of the Bhopal disaster using a system dynamics model to evaluate the safety management system. It highlighted key contributing factors that included faulty safety equipment, insufficient training, deficient decision-making by operators, and a managerial body focused on production at the expense of safety. The study demonstrated how the interconnection of these factors affected the feedback loops within the organization. By simulating the dynamics of these relationships, the research provided valuable insights on how systemic failures in safety management systems can lead to incidents. Additionally, it offered a framework for enhancing safety practices in industrial environments.

Although the research provided valuable insights, its reliance on retrospective analysis introduced biases that may limit the general applicability of its findings. A system dynamics model effectively illustrates relationships; however, it oversimplifies the complexities of real industrial operations and human behavior. The study also lacks empirical validation, which reduces its practical relevance to current safety practices.

Employee Competencies

Competency management ensures that personnel are equipped with the necessary knowledge, skills, and attitudes to perform their roles safely and effectively, yet there is a striking scarcity of studies that examine competency frameworks tailored to the unique demands of AIM and PSM. Works on behavior-based safety [58–61] underscore the value of competency development in achieving safety excellence. Nevertheless, the literature lacks comprehensive analyses of how to tailor and implement AIM- and PSM-specific competencies. This gap highlights the need for empirical research to probe the development, assessment, and continuous improvement of competencies to ensure that personnel are not just technically capable but also adept in identifying and mitigating dynamic risks inherent in their operations.

Research by [62] used the Cognitive Reliability and Error Analysis Method (CREAM) to evaluate human reliability in a Liquefied Petroleum Gas (LPG) company. The research revealed that human errors contribute to operational risks due to organizational shortcomings, cognitive stressors, and external environmental factors. The study highlighted the interplay between human performance, procedural adherence, and systemic feedback loops, revealing how unresolved incidents can escalate to larger systemic failures. The study showed the effectiveness of the CREAM in diagnosing and mapping these interactions, identifying high-risk scenarios, and providing insights for timely interventions. However, the study focused on a specific case (an LPG company) potentially limiting the application of the findings to other industries and contexts. Moreover, the reliance on the CREAM without considerations of external factors such as regulations or market conditions constrains its validation due to a limited contextual application. Additionally, the study leaned more toward quantitative over qualitative insights; this potentially overlooks human and organizational factors.

Organizational Safety Culture

Organizational safety culture, defined as the shared attitudes, values, norms, and practices that influence an organization's approach to risk and safety management, plays a pivotal role in the effectiveness of safety systems. Yet, studies on the nuanced ways in which safety culture influences AIM and PSM practices are lacking. Works like those of [63–66] provide an early discussion on the significance of safety culture. However, there is a scarcity of empirical research that links the specific attributes of a safety culture to successful AIM and PSM. These attributes include leadership commitment, employee engagement, and open communication, underscoring the need for more research in this field.

4.3.4. Integration with Technological Advancements and Industry 4.0

Operators frequently rely on outdated systems for equipment monitoring and risk management instead of adopting advanced technologies. This reluctance is primarily driven by the high costs involved and, in some cases, the challenges or impracticalities of integrating legacy systems with modern technologies. This is evident in older plants, including ADNOC assets located on Das Island, which depend on manual human interventions to activate emergency shutdown systems and to perform integrity inspections. These assets were notably underrepresented at ADIPEC 2024 Energy^{AI}, where AI capabilities were showcased in the automation of asset management [67].

4.3.5. Practical Implementation Guidelines

While conceptual frameworks and theoretical models for AIM and PSM abound, there is a notable scarcity of research focused on providing actionable, step-by-step guidelines that organizations can follow to effectively implement these systems. This gap is particularly evident when it comes to adapting these frameworks to the diverse and complex realities of various industries. For instance, the works by [68–70] offer groundbreaking insights into the design of safety systems; however, they do not translate into detailed strategies for frontline implementation. The diversity of operational, regulatory, and cultural environments across sectors poses a significant challenge to the creation and adoption of universal systems. Studies such as [71–77] highlight the importance of adaptability and sector-specific considerations but fall short of proposing a framework for universal application. This shortfall underscores the need for research to bridge the gap between the high-level principles of safety management and the practicalities of their application in a universally adaptable manner.

4.3.6. Continuous Improvement and Adaptation

While safety management systems acknowledge the importance of continuous improvement practices [73–77], detailed studies focusing on their iterative application in AIM and PSM contexts are lacking. Researchers such as [78,79] explored the role of safety culture in driving continuous improvement, particularly in high-risk industries. They highlighted its importance in fostering a mindset of vigilance, compliance, and proactive risk management. However, significant gaps remain in the literature regarding the specific methodologies needed to effectively capture and disseminate safety culture within AIM and PSM. The absence of detailed frameworks and operational tools to systematically integrate safety culture into these areas limit the ability of most organizations to translate theoretical principles into actionable practices.

Future research should, therefore, prioritize the developing methodologies that facilitate the systematic integration of continuous improvement and adaptability principles to enable organizations to effectively manage the complexities of modern industrial safety challenges.

4.3.7. Data Management and Analytics

AIPS and AIM data integration with industrial resource planning platforms such as SAP and Oracle is scarce in the literature. A study by [80] examined the role of data analytics and integration in risk management; however, these examinations did not provide examples of tools and case studies for such integration. This gap is an opportunity to develop data-driven insights to improve the overall management of safety and integrity in industrial operations. Integration platforms such as the AVEVA Unified Operations Center [81] can be used to link AIM and PSM data with industrial enterprise resource planning (ERP) tools.

However, these systems come with challenges that include high implementation costs, integration with legacy systems, data synchronizing across integrated platforms, and cyber security vulnerabilities.

4.4. Proposed Strategies for Effective AIM and PSM Implementation

To achieve a mature AIM and PSM implementation, a structured maturity four-phased model of Plan, Access, Validate, and Report, presented by Figure 6, was developed for each of the proposals to address the above-identified gaps. These phases create a scalable, iterative process that fosters a sustainable strategy for implementation and organizational excellence.

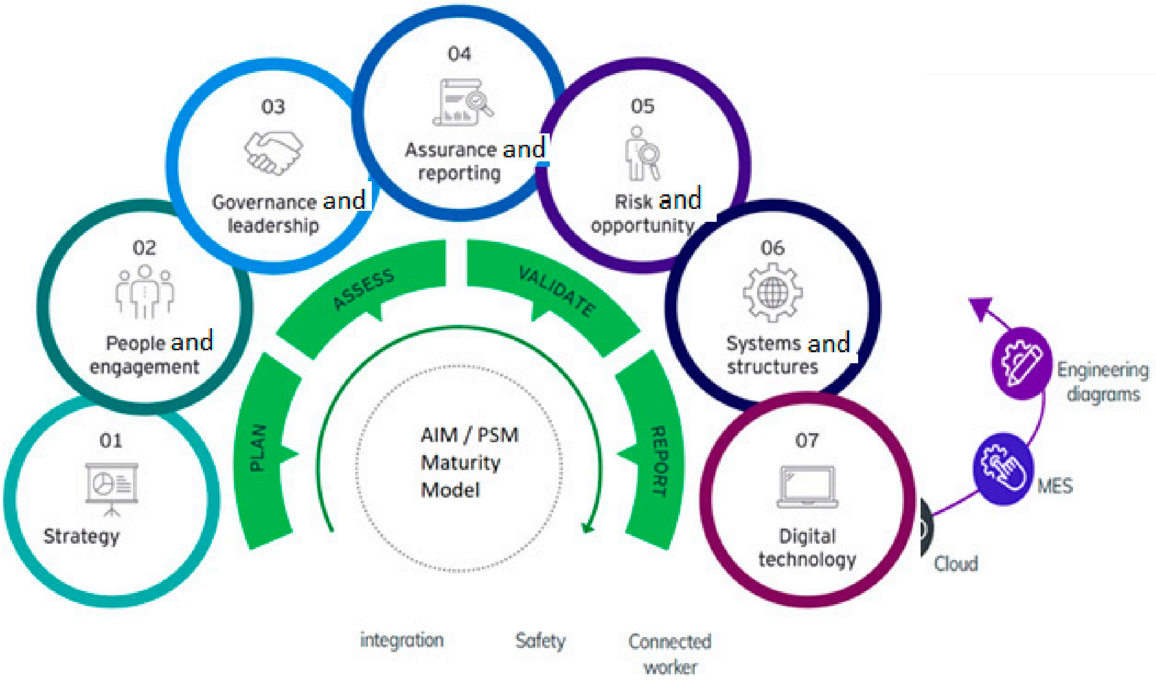

Figure 6. Proposed AIM and PSM maturity model [82,83].

The Plan phase involves establishing a clear vision, aligning organizational objectives, and engaging stakeholders for collaboration and ownership. The Access phase will establish robust governance frameworks with leadership overseeing decision-making to ensure compliance. Compliance mechanisms can be through assurance mechanisms such as audits and performance reviews. The Validate phase will assess risks and opportunities through evaluations, the identification of barriers, and refining the strategies with contingency measures. Finally, the Report phase will leverage digital technologies and AI for data analysis, performance tracking, and decision-making. Research by [82,83] demonstrated that these principles enhance performance and foster a proactive culture and sustainable success, building a strong foundation for a long-term competitive advantage.

4.4.1. Robust Risk Assessment and Management

A comprehensive risk assessment process is crucial for identifying and mitigating potential hazards. This is one motivation for the integration of AIM and PSM to allow for a more holistic view of both the safety and integrity aspects of operations. The use of data-driven approaches, such as real-time monitoring systems and predictive modeling, can provide invaluable insights for proactive decision-making. This is best practice and a necessity in the current industrial landscape, where dynamic operational environments are the norm.

4.4.2. Training and Competency Development

The successful implementation of AIM and PSM systems requires a well-trained and competent workforce. Comprehensive training programs and competency development initiatives enhance the capabilities of personnel in handling uncertainties effectively. Equipping employees with the necessary knowledge and skills enables them to identify and manage risks and respond to unexpected events. Training programs can cover a wide range of areas, including process safety, asset inspection and maintenance, emergency response protocols, and the use of advanced monitoring and diagnostic tools. Furthermore, investing in the training and development of personnel fosters a behavioral change that drives the development of the safety culture needed.

4.4.3. Regulatory Compliance and Enforcement

Comprehensive regulatory frameworks should mandate that industries demonstrate the establishment of a Health and Safety Management System that complies with recognized frameworks, such as OSHA's 29 CFR 1910.119 or EU Seveso III Directive for PSM and ISO 55001 for AIM, as a prerequisite for obtaining operating licenses. Additionally, pre-licensing audits and the periodic submission of hazard assessments to regulatory authorities should be mandated as integral components of compliance monitoring.

Regulatory frameworks must be dynamic and adaptable to changing industry trends, technological advancements, and emerging risks. The fast-paced evolution of the industry, especially with the advent of digital technologies and the IoT, necessitates regular reviews and updates of regulations to ensure their continued relevance and effectiveness. This adaptability will address the complexities and nuances of modern petrochemical operations, ensuring that safety and integrity management align with technological progress and emerging challenges.

4.4.4. Integration of Digital Technologies

AI algorithms can empower decision-making processes through the extraction of valuable insights from the collected data. Section 4.2.4 gives valuable insights into the role of Industry 4.0 applications including their predictive capabilities, which can enable proactive maintenance interventions, reducing the likelihood of unexpected failures and disruptions.

The digitalization of systems can facilitate the implementation of remote monitoring and control capabilities. Real-time data transmission and remote access to critical systems empower operators and decision-makers to monitor asset performance, identify abnormal conditions, and take prompt actions regardless of their physical location. This remote monitoring capability increases operational efficiency, reduces the response time to uncertainties, and enhances the overall risk management. Moreover, digital platforms and cloud-based solutions enable centralized data storage, easy accessibility, and efficient collaboration among various stakeholders, as shown in Figure 7. With adequate cybersecurity measures, this can facilitate seamless information sharing, improve communication, and enhance collaboration among various departments and teams involved in the implementation of AIM and PSM systems [84,85].

The illustrated concept is in its infancy, representing a collaboration between the author's oil and gas company and an IT service provider to harness the capabilities of AI to integrate multiple company work streams. Of relevance to this work is enhancing AIM and PSM by streamlining the management of safety-critical equipment through work schedule optimization and consolidating Process Safety Performance metrics from eight operating sites distributed across the country.

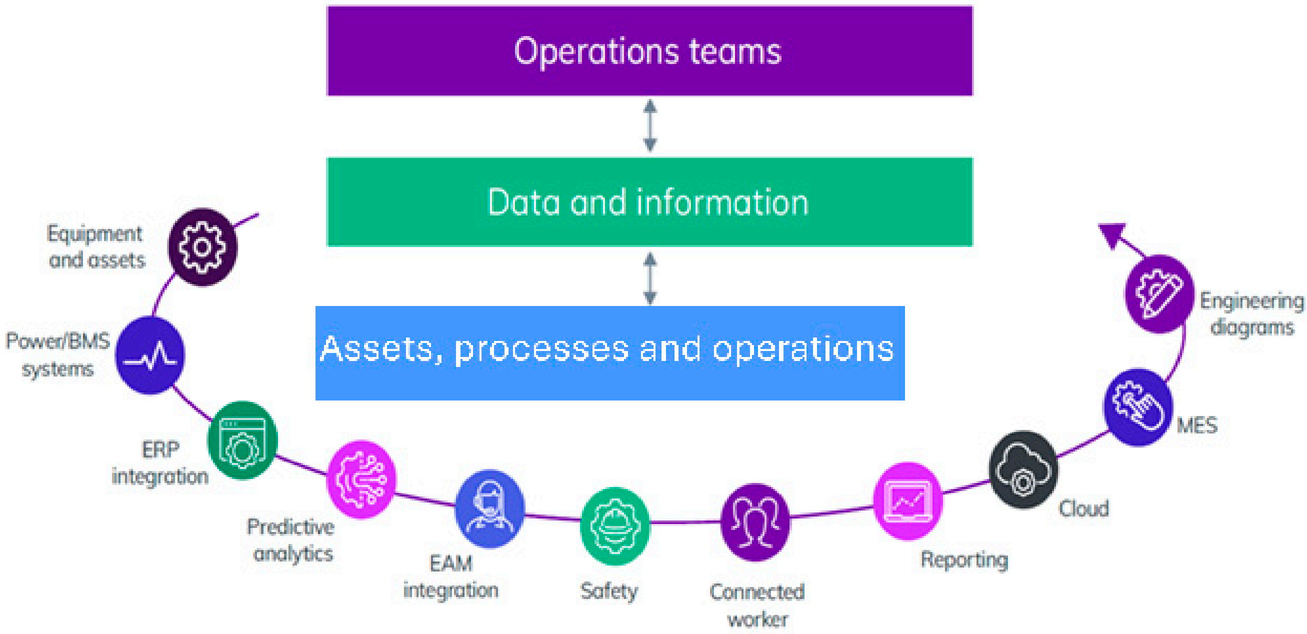

Figure 7. Integration concept for business work streams. KEY: EAM—Enterprise Asset Management; ERP—enterprise resource planning (SAP); BMS—Battery Management System; and MES—Manufacturing Execution System.

4.4.5. Collaboration and Knowledge Sharing

This can be though merging cross-functional skills to have a holistic mindset in risk management, for example, by managing AIM with a PSM mindset as advocated by [86]. Operators, who are at the forefront, can share practical field insights, lessons learned, and real-world case studies. This information exchange can allow others in similar industries to understand encountered challenges, strategies adopted, and potential pitfalls to avoid. Industrial collaboration in these fields can foster a learning culture to enhance risk management.

Industrial associations focusing on integrated AIM and PSM systems can provide platforms for stakeholders to come together, exchange ideas, and collectively address shared challenges. Through conferences, workshops, and forums, these associations can provide a platform for networking, knowledge sharing, and the dissemination of best practices to each other. Collaborations can create supportive environments that foster resilience in the industry, promote positive safety cultures, and drive innovation for continuous improvement [87].

4.5. Conceptual Integrated AIM and PSM Framework

This section introduces an integrated conceptual framework for AIM and PSM, depicted by Figure 8. To achieve a comprehensive approach, the framework systematically addresses the identified gaps in the existing literature and the current industrial practices by integrating them into its structure.

The integrated framework was arrived at by first incorporating the common PSM systems in the industry with the AIM ISO 55001 elements in Table 1, together with the identified gaps in industrial practices and in the literature. The framework was termed the "integrated asset integrity and process safety Management (iAIPSM) system" and introduces (1) cultural and organizational barriers, (2) regulatory frameworks, (3) technological advancements and Industry 4.0, (4) universal implementation guidelines, and (5) data management and analytics as the new elements.

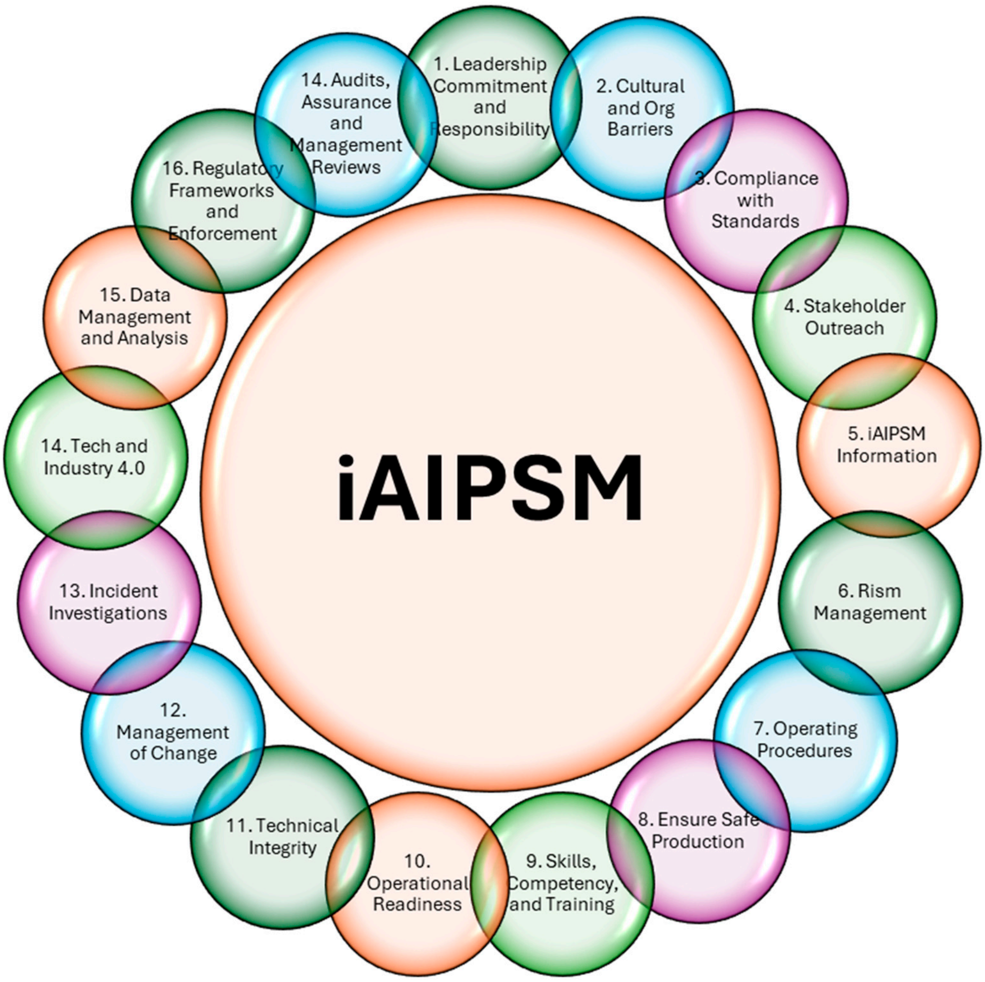

Figure 8. Proposed iAIPSM conceptual framework.

4.5.1. iAIPSM Element 1: Leadership Commitment and Responsibility

Leadership commitment and responsibility are the drivers for navigating the complexities and challenges of AIM and PSM to steer organizations towards operational excellence and sustainable practices. Sustainable development necessitates a leadership paradigm that focuses on safety, environmental stewardship, and social equity. This is a shift from focusing on short-term profiteering and immediate business interests to focusing on broader societal and environmental concerns.

Leadership responsibility includes the ethical governance of operations and the advancement of a positive safety culture. The ethical dimension of leadership involves making decisions that reflect integrity, transparency, and accountability. Additionally, advocating for the establishment of a strong safety culture is a reflection of a leadership's commitment to prioritizing the well-being of employees and communities over operational productivity. Moreover, the drive towards innovation for sustainable practices requires visionary leadership that embraces change and seeks to redefine the industry's future [88–91].

4.5.2. iAIPSM Element 2: Cultural and Organizational Barriers

The pervasive influence of cultural and structural barriers on the efficacy of safety and integrity management systems underscores the complex interplay between human factors and organizational structures. However, neither the PSM nor AIM systems fully address organizational culture and embedded structural barriers. For instance, the CCPS RBPSM "process safety culture" element refers to the values, beliefs, and norms that are shared by individuals within an organization regarding safety practices and behaviors. It comprises the organization's commitment to safety, the attitudes of employees towards safety, and the way safety is integrated into everyday operations. The CCPS RBPSM "workforce involvement" element encourages engagement at all levels of an organization in safety and integrity decisions [92].

4.5.3. iAIPSM Element 3: Compliance with Standards

This element dictates how industries must operate to adhere to established design codes and international standards. These include the American Petroleum Institute (API), American Society of Mechanical Engineers (ASME), and International Organization for Standardization (ISO) standards and the National Fire Protection Association (NFPA) codes. These standards encapsulate the cumulative knowledge and best practices developed through years of industry experience and research.

Moreover, aligning with these standards facilitates continuous improvement and operational excellence through the adoption of proven methodologies and technologies. This alignment involves regular audits, certifications, and reviews that encourage organizations to continually evaluate and upgrade their safety and asset management practices.

4.5.4. iAIPSM Element 4: Stakeholder Outreach

Stakeholder outreach plays a pivotal role in establishing a transparent, inclusive, and collaborative environment. This facet of iAIPSM includes the systematic engagement of all parties impacted by or having interests in the operational integrity and safety of a facility. These include employees, local communities, regulators, industry groups, and shareholders. The primary objective of stakeholder outreach is to foster open communication and partnership to ensure that all are well informed, their concerns are addressed, and their contributions are integrated in management strategies.

Academic research supports the importance of stakeholder outreach in PSAIM, arguing that successful stakeholder involvement promotes better safety performance and operational resilience. Furthermore, empirical research by [93] on corporate social responsibility (CSR) indicates that incorporating stakeholder perspectives into AIM and PSM practices addresses ethical concerns to support strategic business goals. Through this lens, stakeholder outreach transcends its traditional boundary as a regulatory and ethical requirement, evolving into a strategic asset to propel organizations towards operational excellence and sustainable development.

4.5.5. iAIPSM Element 5: iPSAIM Information

iAIPSM information is a collection of data, documents, and details regarding the chemicals used, the process technologies employed, and the equipment utilized within a facility. According to the CCPS and OSHA, the thorough management and accessibility of iAIPSM information are pivotal for conducting effective process hazard analyses (PHAs), thereby enabling the identification, assessment, and mitigation of risks. Furthermore, iAIPSM information is instrumental in the development and implementation of operational controls, safety systems, and emergency response protocols, ensuring that personnel are well informed of the hazards and the measures in place to control such risks [94–96].

4.5.6. iAIPSM Element 6: Risk Management

Risk management embodies a systematic approach to identifying, assessing, and controlling risks to make them as low as reasonably practicable (ALARP). This dynamic process involves a series of steps of risk identification, analysis, evaluation, and the implementation of mitigation strategies.

Within the iAIPSM framework, risk management is for incident prevention beyond the traditional hazard identification and control techniques and includes holistic risk management methodologies that incorporate organizational, technical, and human factors as well as harnessing the powers of AI [97,98].

4.5.7. iAIPSM Element 7: Operating Procedures

These procedures are a detailed set of instructions and guidelines designed to manage the operational phases of process units, from the startup to normal operations, shutdowns, and emergencies, and handle specific operational modes that may pose increased risks. The development, implementation, and management of these procedures are mandated by regulatory bodies such as the OSHA under PSM regulations. By standardizing operations, these procedures mitigate the potential for human error and enhance the predictability and stability of processes.

Well-documented procedures support effective training and competency development among personnel, improving their ability to respond adeptly to both routine and non-routine operational scenarios. Furthermore, the dynamic nature of operating procedures advocates for their continuous review and improvement considering operational experiences, technological advancements, and process modifications. This is to ensure that procedures remain relevant.

4.5.8. iAIPSM Element 8: Ensure Safe Production (ESP)

"Ensure Safe Production", also referred to as "the conduct of operations", is a multifaceted approach designed to carefully control the routine actions of frontline personnel to ensure operational safety. This principle, illustrated by Figure 9, integrates nine layers supporting each other to ensure consistent operations within safe limits for operational excellence [99].

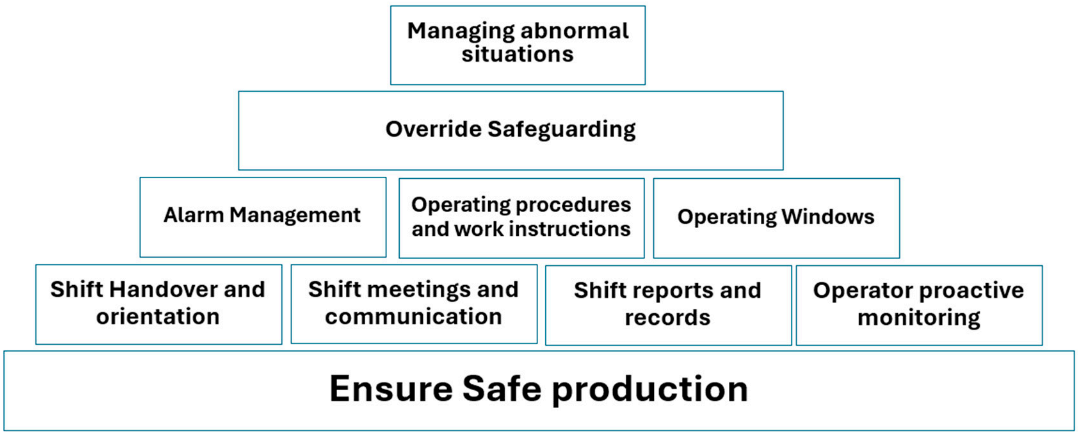

Figure 9. Ensure safe production.

4.5.9. iAIPSM Element 9: Skills, Competency, and Training

This trinity addresses the need for a workforce that is proficient in technical skills and possesses a deep understanding of safety principles, risk management practices, and emergency response procedures. The development of competencies and the provision of continuous training are fundamental for ensuring that employees can identify hazards, understand the operational controls that are in place, and take appropriate actions to mitigate risks. Regulatory bodies, such as the OSHA and CCPS, emphasize investing in competency development and training. These elements are central for fostering a culture of safety and enhancing decision-making.

4.5.10. iAIPSM Element 10: Operational Readiness

This is to ensure that facilities, systems, and personnel are fully prepared to commence and sustain operations at the desired levels of safety and performance from the very outset. This concept covers a comprehensive review and verification process that ensures all elements of an operation, ranging from equipment and systems to procedures and human resources, are aligned with safety standards and operational requirements before the initiation of operations. Operational readiness is particularly important during the commissioning and startup phases of a project, where the potential for deviations from design intentions to actual operational conditions is high. Ref. [100] explored the relationship between operational readiness processes and a reduction in safety incidents, highlighting the effectiveness of proactive measures in identifying and addressing potential safety issues before they escalate into actual incidents. Furthermore, the integration of operational readiness into the broader framework of iAIPSM emphasizes the interconnectedness of safety, reliability, and efficiency. This interconnectivity showcases that comprehensive operational readiness reviews are strategic investments in the long-term viability of operations.

4.5.11. iAIPSM Element 11: Technical Integrity

This element will focus on the identification and quality assurance of critical equipment and systems. This is partially addressed by the EI PSM (UK/EU). The identification and integrity assurance of safety-critical equipment and systems (SCESs) serves as a linchpin safeguard against catastrophic failures. Though the EI PSM (UK/EU) lays the foundations for the management of SCESs, the system falls short of detailing their identification mechanism. SCES identification distinguishes those assets and systems whose failure could precipitate significant hazardous events. A SCES integrity assurance process entails a comprehensive regimen of inspection, testing, maintenance, and validation activities designed to establish confidence that these components function within their specified safety parameters throughout their operational lifecycle. Furthermore, the deployment of reliability-centered maintenance (RCM) strategies, as discussed by [101], provides a structured approach to prioritizing maintenance efforts based on equipment criticality and failure impact analysis. This focus on safety-critical equipment and systems drives compliance with regulatory and industry standards in addition to fortifying operational resilience against unforeseen disruptions.

4.5.12. iAIPSM Element 12: Management of Change

The management of change (MOC) ensures that changes to processes, equipment, materials, chemicals, and personnel are assessed, managed, and documented to maintain the required safety and integrity levels. The MOC is vital for identifying potential hazards and evaluating the risk implications of changes before their implementation. The MOC process includes a wide range of changes, including modifications to process conditions, the alterations of operating procedures, the introduction of new materials, and changes to personnel. The CCPS and OSHA mandate a rigorous MOC process to sustain operational safety and to prevent incidents.

Studies have demonstrated that a well-implemented MOC process not only prevents safety incidents but also contributes to operational efficiency and reliability. Ref. [102] provides a detailed, step-by-step framework for incorporating risk management practices, including process hazard analysis (PHA), into management of change (MOC) procedures for systematic process risk management. Furthermore, the MOC process can ensure that stakeholders are informed about changes and their implications.

4.5.13. iAIPSM Element 13: Incident Investigations

Incident investigations involve the systematic, detailed examination of incidents to identify the root causes and their contributing factors. These range from technical failures to human errors and deficiencies in the management system. The primary objective of incident investigations is to uncover underlying systemic vulnerabilities that compromise safety and integrity without attributing blame. Ref. [103] examined the factors that influence incident investigations and learning from them. The study identified 42 facilitators and 28 barriers, which were organized into the four key dimensions of (1) participants, (2) the input, (3) the process, and (4) the context. The review emphasized the role of robust reporting systems, thorough investigations, a supportive organizational learning culture, and effective cross-industry knowledge exchange. Challenges such as a blame culture, underreporting, and superficial incident investigations were highlighted as the main obstacles.

4.5.14. iAIPSM Element 14: Technological Advancements and Industry 4.0

This will incorporate the role of emerging technologies and industrial advancements in enhancing safety and integrity management practices. These technologies offer unparalleled opportunities for improving the monitoring, maintenance, and management of SCESs. Furthermore, the application of AI and ML algorithms can enhance the identification and assessment of risks by analyzing vast datasets to detect patterns and predict potential failures before they occur.

4.5.15. iAIPSM Element 15: Data Management and Analytics

Effective data management is the ability to capture, store, update, and retrieve vast volumes of operational and safety-related data. Analytics, on the other hand, leverages these data through sophisticated algorithms and statistical methods to identify patterns, predict potential failures, and optimize safety and integrity strategies. The incorporation of data management and analytics into iAIPSM systems is indispensable, given the increasingly complex and data-intensive nature of industrial operations. Moreover, the advent of Industry 4.0 technologies further accentuates the value of data management and analytics. This synergy between data management and analytics will facilitate a proactive approach to safety, moving beyond reactive measures to anticipate and mitigate risks before they manifest into incidents.

4.5.16. iAIPSM Element 16: Regulatory Frameworks and Enforcement

Regulatory frameworks through legislation, standards, and guidelines will establish the minimum requirements for managing the integrity of operational processes and the safety of assets to set a baseline for industrial practices. These are instrumental in delineating the responsibilities of organizations, promoting best practices, and ensuring that safety considerations are integrated into all phases of asset lifecycle management.

On the other hand, enforcement mechanisms provide the means through which compliance with regulations can be monitored, non-compliance detected, and corrective actions mandated. Such mechanisms often involve regular inspections, audits, and the imposition of penalties for violations, which collectively act to ensure that organizations adhere to established safety and integrity standards. The presence of stringent enforcement measures is associated with higher levels of compliance and has been linked to improvements in safety outcomes and reductions in incident rates within various industries. Furthermore, such frameworks will facilitate a level playing field among industry participants, ensuring that competitive pressures do not lead to compromises in safety standards.

To support regulatory frameworks and enforcement, there is a need for a practical universal implementation guideline for iAIPSM. Practical implementation guidelines will bridge abstract safety concepts and their real-world applications, providing clear, actionable steps that organizations can follow to manage risks and maintain the integrity of assets.

4.5.17. iAIPSM Element 17: Audits, Assurance, and Management Reviews

Audits, assurance, and management reviews are guided by internationally recognized standards, such as the ISO 19011 recommendations. These offer guidance on auditing management systems to establish compliance with established standards and procedures. Audits, in this context, will be a systematic and controlled process to determine compliance with the requirements of all the preceding 16 elements. According to [56], audits evaluate the effectiveness of the established controls, adherence to best practices, and compliance with regulatory standards. These evaluations allow organizations to spot inconsistencies and take corrective action for improvements.

On the other hand, assurance activities complement audits by providing continual review and verification to guarantee that management systems work as intended. For iAIPSM, assurance will entail evaluating the established management systems and methods and their capabilities to effectively manage risks. These actions will give stakeholders confidence that management methods are effective and meet industry requirements.

4.6. Contributions

This review represents a seminal contribution to the fields of AIM and PSM by examining and proposing solutions to identified gaps in both industry practices and the academic literature. The work evaluates the lack of integration between AIM and PSM systems, highlighting the necessity for a unified approach that aligns risk management with the maintenance of asset integrity. It proposes an integrated framework that synergizes these domains, thereby enhancing operational safety and reliability. Moreover, the research identifies the absence of robust, comprehensive regulatory frameworks and consistent enforcement mechanisms as the major gaps. It advocates for the development and implementation of stringent regulations and enforcement practices that are adaptable to technological and operational advancements, thereby ensuring higher compliance and safety standards.

This research delves into the cultural and organizational barriers that impede the effective implementation of AIM and PSM and suggests strategies for cultivating a positive culture and structures that support safety as a core value.

Subsequently, the research acknowledges the rapid pace of technological advancements in the advent of Industry 4.0, recognizing their potential to transform AIM and PSM practices.

4.7. Limitations of the Study

Inherent limitations associated with a systematic literature review (SLR) methodology are notable limitations. A SLR is inherently susceptible to publication bias, where studies with positive findings are more likely to be published than those with negative or inconclusive results, potentially skewing the review outcomes [104–106]. The stringent inclusion and exclusion criteria fundamental to the SLR methodology may inadvertently omit relevant studies that do not meet these predefined criteria. This might lead to a narrow scope to capture the full spectrum of available evidence [107–111]. Consequently, SLRs may suffer from the challenges of managing vast amounts of data, especially in areas with extensive literature, which can complicate the synthesis and interpretation of the findings [112–114].

The limitation of relying on ISO 55001 as the main AIM reference is based on its broad strategic focus, which may not have the operational depth provided by other methodologies. Other methodologies and systems that could complement ISO 55001 include (i) Total Productive Maintenance (TPM); (ii) reliability-centered maintenance (RCM); (iii) Lean

Maintenance (LM), and (iv) Six Sigma for Maintenance. Each of these systems offers unique insights and tools for specific aspects of AIM that are not covered by ISO 55001.

5. Conclusions

This work offers a thorough analysis of asset integrity management (AIM) and process safety management (PSM) systems. Historical fragmentation between AIM and PSM was addressed by combining their individual components into a unified system that integrates technical and operational elements, leading to an integrated framework called iAIPSM. A theoretical basis for iAIPSM was developed by synthesizing findings from over 100 academic and industry sources to provide practical insights into its application.

The framework introduces key features, including cultural and organizational factors, advanced technological solutions, and stakeholder engagement, to create a holistic approach to risk management and bolstering operational resilience. By leveraging advanced technologies such as artificial intelligence, machine learning, and predictive analytics, iAIPSM facilitates real-time monitoring, predictive maintenance, and data-driven decision-making capabilities to support sustainability in complex industrial environments.

This study's strength lies in its alignment with global sustainability objectives. The iAIPSM framework directly advances several United Nations Sustainable Development Goals (SDGs), notably SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), highlighting its far-reaching socioeconomic and environmental relevance.

The proposed iAIPSM framework serves as a strategic roadmap toward safer, more reliable, and environmentally responsible operations. Future research should focus on validating the iAIPSM framework through real-world case studies and exploring innovative technologies to further enhance its potential.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17010286/s1, PRISMA Checklist. Reference [115] is cited in Supplementary Materials.

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References

1. Nwankwo, C.D.; Theophilus, S.C.; Arewa, A.O. A comparative analysis of process safety management (PSM) systems in the process industry. *J. Loss Prev. Process Ind.* **2020**, *66*, 104171. [CrossRef]
2. Al-Douri, A.; El-Halwagi, M.M.; Groth, K.M. Emergency shutdowns of propylene production plants: Root cause analysis and availability modeling. *J. Loss Prev. Process Ind.* **2022**, *80*, 104921. [CrossRef]
3. Behie, S.W.; Halim, S.Z.; Efaw, B.; O'Connor, T.M.; Quddus, N. Guidance to improve the effectiveness of process safety management systems in operating facilities. *J. Loss Prev. Process Ind.* **2020**, *68*, 104257. [CrossRef] [PubMed]

4. Khan, F.; Yarveisy, R.; Abbassi, R. Risk-based pipeline integrity management: A road map for the resilient pipelines. *J. Pipeline Sci. Eng.* **2021**, *1*, 74–87. [CrossRef]
5. Khan, F.; Amyotte, P.; Adedigba, S. Process safety concerns in process system digitalization. *Educ. Chem. Eng.* **2021**, *34*, 33–46. [CrossRef]
6. Bhusari, A.; Goh, A.; Ai, H.; Sathanapally, S.; Jalal, M.; Mentzer, R.A. Process safety incidents across 14 industries. *Process Saf. Prog.* **2021**, *40*, e12158. [CrossRef]
7. Amyotte, P.R.; Khan, F.I. The role of inherently safer design in process safety. *Can. J. Chem. Eng.* **2021**, *99*, 853–871. [CrossRef]
8. HID CI5A. Guidance on ALARP Decisions in COMAH. Available online: https://www.hse.gov.uk/foi/internalops/hid_circs/permissioning/spc_perm_37/ (accessed on 28 August 2024).
9. Yakoot, M.S.; Elgibaly, A.A.; Ragab, A.M.; Mahmoud, O. Well integrity management in mature fields: A state-of-the-art review on the system structure and maturity. *J. Pet. Explor. Prod.* **2021**, *11*, 1833–1853. [CrossRef]
10. Rachman, A.; Zhang, T.; Ratnayake, R.C. Applications of machine learning in pipeline integrity management: A state-of-the-art review. *Int. J. Press. Vessel. Pip.* **2021**, *193*, 104471. [CrossRef]
11. Iaiani, M.; Tugnoli, A.; Macini, P.; Cozzani, V. Outage and asset damage triggered by malicious manipulation of the control system in process plants. *Reliab. Eng. Syst. Saf.* **2021**, *213*, 107685. [CrossRef]
12. Eltervåg, A.; Hansen, T.B.; Lootz, E.; Rasmussen, E.; Sørensen, E.; Johnsen, B.; Heggland, J.E.; Lauridsen, Ø.; Ersdal, G. Principles for Barrier Management in the Petroleum Industry. *Pet. Saf. Auth. Nor.* **2017**, preprint.
13. Schmitz, P.; Swuste, P.; Reniers, G.; van Nunen, K. Mechanical integrity of process installations: Barrier alarm management based on bowties. *Process Saf. Environ. Prot.* **2020**, *138*, 139–147. [CrossRef]
14. Park, S.; Xu, S.; Rogers, W.; Pasman, H.; El-Halwagi, M.M. Incorporating inherent safety during the conceptual process design stage: A literature review. *J. Loss Prev. Process Ind.* **2020**, *63*, 104040. [CrossRef]
15. IOGP Safety Performance Indicators—2023 Data (2024) IOGP Publications Library. Available online: https://www.iogp.org/bookstore/product/iogp-safety-performance-indicators-2023-data/ (accessed on 6 December 2024).
16. IChemE. *Lessons Learned Database*; IChemE: Melbourne, Australia, 2013. Available online: https://www.icheme.org/knowledge-networks/communities/special-interest-groups/safety-and-loss-prevention/resources/lessons-learned-database/ (accessed on 9 September 2024).
17. Rodríguez, J.M.; Payne, S.C.; Bergman, M.E.; Beus, J.M. The impact of the BP Baker report. *J. Saf. Res.* **2011**, *42*, 215–222. [CrossRef]
18. Kletz, T. *Lesson from Disaster: How Organizations Have No Memory and Accidents Recur*; IChemE: Melbourne, Australia, 1993; pp. 1–183.
19. Aschenbrenner, S. *Failure Modes, Effects and Diagnostic Analysis, Project: Mechanically Actuated Valves, Direct Operated Solenoid Valves, Pneumatically Operated Valves and Pilot Operated Solenoid Valves*; Exida: Singapore, 2016; pp. 1–71.
20. Kumar, R. *Research Methodology: A Step-by-Step Guide for Beginners*; Sage Publications Limited: London, UK, 2019.
21. Newman, M.; Gough, D. *Systematic Reviews in Educational Research: Methodology, Perspectives and Application*; Springer: Berlin/Heidelberg, Germany, 2020.
22. Tricco, A.C.; Lillie, E.; Zarin, W.; O'Brien, K.K.; Colquhoun, H.; Levac, D.; Moher, D.; Peters, M.D.J.; Horsley, T.; Weeks, L.; et al. Prisma extension for scoping reviews (PRISMA-SCR): Checklist and explanation. *Ann. Intern. Med.* **2018**, *169*, 467–473. [CrossRef] [PubMed]
23. *ISO 55001*; Asset Management—Management Systems—Requirements. International Organization for Standardization: Geneva, Switzerland, 2014.
24. Ahuja, I.S. Total productive maintenance practices in manufacturing organisations: Literature review. *Int. J. Technol. Policy Manag.* **2011**, *11*, 117–138. [CrossRef]
25. Braaksma, A.J.J.; Klingenberg, W.; Veldman, J. Failure mode and effect analysis in asset maintenance: A multiple case study in the process industry. *Int. J. Prod. Res.* **2013**, *51*, 1055–1071. [CrossRef]
26. Ratnayake, R.C.; Chaudry, O. Maintaining sustainable performance in operating petroleum assets via a lean-six-sigma approach: A case study from engineering support services. *Int. J. Lean Six Sigma* **2017**, *8*, 33–52. [CrossRef]
27. Karthi, S.; Devadasan, S.R.; Murugesh, R. Integration of Lean Six-Sigma with ISO 9001: 2008 standard. *Int. J. Lean Six Sigma* **2011**, *2*, 309–331. [CrossRef]
28. AIChE. *Guidelines for Risk Based Process Safety*; AIChE: New York, NY, USA, 2023; Available online: https://www.aiche.org/ccps/resources/publications/summaries/guidelines-risk-based-process-safety (accessed on 10 September 2024).
29. Bernstein, S. The United Nations and the governance of Sustainable Development Goals. *Gov. Through Goals* **2017**, preprint. [CrossRef]
30. Tsolakis, N.; Niedenzu, D.; Simonetto, M.; Dora, M.; Kumar, M. Supply network design to address United Nations Sustainable Development Goals: A case study of blockchain implementation in Thai fish industry. *J. Bus. Res.* **2021**, *131*, 495–519. [CrossRef]

31. Fraga-Lamas, P.; Fernández-Caramés, T.M. Leveraging blockchain for sustainability and open innovation: A cyber-resilient approach toward EU Green Deal and UN Sustainable Development Goals. In *Computer Security Threats*; IntechOpen: Rijeka, Croatia, 2020.
32. Usiabulu, G.I.; Amadi, A.H.; Adebisi, O.; Ifedili, U.D.; Ajayi, K.E.; Moses, P.R. Gas Flaring, and Its Environmental Impact in Ekpan Community, Delta State, Nigeria. *Am. J. Sci. Eng. Technol.* **2023**, *8*, 42–53.
33. Simayi, M.; Hao, Y.; Li, J.; Shi, Y.; Ren, J.; Xi, Z.; Xie, S. Historical volatile organic compounds emission performance and reduction potentials in China's petroleum refining industry. *J. Clean. Prod.* **2021**, *292*, 125810. [CrossRef]
34. Mandal, T.; Yadav, P.; Kumar, M.; Lal, S.; Soni, K.; Yadav, L.; Saharan, U.S.; Sharma, S. Characteristics of volatile organic compounds (VOCs) at an urban site of Delhi, India: Diurnal and seasonal variation, sources apportionment. *Urban Clim.* **2023**, *49*, 101545. [CrossRef]
35. Ali, M.U.; Liu, G.; Yousaf, B.; Ullah, H.; Abbas, Q.; Munir, M.A.M. A systematic review on global pollution status of particulate matter-associated potential toxic elements and health perspectives in urban environment. *Environ. Geochem. Health* **2019**, *41*, 1131–1162. [CrossRef]
36. Wang, S.; Wang, G.; Xiao, Y. How environmental policies affect personal willingness to pay for environmental protection: An investigation of interpretative and resource effects. *Environ. Dev. Sustain.* **2022**, *26*, 1591–1613. [CrossRef]
37. Mannan, M.S.; Reyes-Valdes, O.; Jain, P.; Tamim, N.; Ahammad, M. The evolution of process safety: Current status and future direction. *Annu. Rev. Chem. Biomol. Eng.* **2016**, *7*, 135–162. [CrossRef]
38. Khan, F.I.; Haddara, M.M. Risk-based maintenance (RBM): A quantitative approach for maintenance/inspection scheduling and planning. *J. Loss Prev. Process Ind.* **2003**, *16*, 561–573. [CrossRef]
39. Yuan, S.; Reniers, G.; Yang, M. Dynamic-risk-informed safety barrier management: An application to cost-effective barrier optimization based on data from multiple sources. *J. Loss Prev. Process Ind.* **2023**, *83*, 105034. [CrossRef]
40. Çakıt, E.; Jan Olak, A.; Murata, A.; Karwowski, W.; Alrehaili, O.; Marek, T. Assessment of the perceived safety culture in the petrochemical industry in Japan: A cross-sectional study. *PLoS ONE* **2019**, *14*, e0226416. [CrossRef] [PubMed]
41. Gatzert, N.; Schmit, J.T.; Kolb, A. Assessing the risks of insuring reputation risk. *J. Risk Insur.* **2016**, *83*, 641–679. [CrossRef]
42. Birkland, T.A. Learning from catastrophes: Strategies for reaction and response—Edited by Howard Kunreuther and Michael Useem. *Public Adm.* **2011**, *89*, 1201–1203. [CrossRef]
43. Picón, E.B.; González, J.A.; Pérez-Albert, Y.; Gheitasi, M. Public risk perception of the petrochemical industry, measured using a public participation geographic information system: A case study of camp de tarragona (Spain). *Environments* **2023**, *10*, 36. [CrossRef]
44. Gambo, N.; Musonda, I. Effect of the fourth Industrial Revolution on road transport asset management practice in Nigeria. *J. Constr. Dev. Ctries.* **2021**, *26*, 19–43. [CrossRef]
45. Gooneratne, C.P.; Magana-Mora, A.; Otalvora, W.C.; Affleck, M.; Singh, P.; Zhan, G.D.; Moellendick, T.E. Drilling in the fourth industrial revolution—Vision and challenges. *IEEE Eng. Manag. Rev.* **2020**, *48*, 144–159. [CrossRef]
46. Tao, F.; Cheng, J.; Qi, Q.; Zhang, M.; Zhang, H.; Sui, F. Digital twin-driven product design, manufacturing and service with Big Data. *Int. J. Adv. Manuf. Technol.* **2023**, *94*, 3563–3576. [CrossRef]
47. Atzori, L.; Iera, A.; Morabito, G. The internet of things: A survey. *Comput. Netw.* **2010**, *54*, 2787–2805. [CrossRef]
48. Kenan, S.; Kadri, S. Process Safety Leading Indicators Survey- February 2013: Center for Chemical Process Safety-White Paper. *Process Saf. Prog.* **2014**, *33*, 247–258. [CrossRef]
49. Mendeloff, J.; Han, B.; Fleishman-Mayer, L.A.; Vesely, J.V. Evaluation of process safety indicators collected in conformance with ANSI/API Recommended Practice 754. *J. Loss Prev. Process Ind.* **2013**, *26*, 1008–1014. [CrossRef]
50. Gawish, M.; Smith, D. Monitoring the health of the asset integrity management system through the use of generic KPIs. In Proceedings of the SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility, Stavanger, Norway, 11–13 April 2016. [CrossRef]
51. CCPS. *Process Safety Leading and Lagging Metrics*; The Center for Chemical Process Safety (CCPS®): New York, NY, USA, 2021. Available online: https://www.aiche.org/sites/default/files/docs/pages/CCPS_ProcessSafety_Lagging_2011_2-24.pdf (accessed on 6 December 2024).
52. Alnoukari, M. From business intelligence to Big Data. In *Research Anthology on Big Data Analytics, Architectures, and Applications*; IGI Global Scientific Publishing: Hershey, PA, USA, 2022; pp. 823–841. [CrossRef]
53. Zhou, K.; Liu, T.; Zhou, L. Industry 4.0: Towards future industrial opportunities and challenges. In Proceedings of the 2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD), Zhangjiajie, China, 15–17 August 2015. [CrossRef]
54. Filus, J.K.; Filus, L.Z. Modeling reliability of systems with repair by stochastic processes with long memory. In *Safety and Reliability of Systems and Processes, Proceedings of the Summer Safety and Reliability Seminar 2023, Kraków, Poland, 9–14 July 2023*; Gdynia Maritime University: Gdynia, Poland, 2023; pp. 69–78. [CrossRef]
55. Yuan, S.; Yang, M.; Reniers, G. Integrated Process Safety and process security risk assessment of industrial cyber-physical systems in Chemical plants. *Comput. Ind.* **2024**, *155*, 104056. [CrossRef]

56. Reason, J. The contribution of latent human failures to the breakdown of Complex Systems. In *Human Error in Aviation*; Routledge: London, UK, 2017; pp. 5–14. [CrossRef]
57. Di Nardo, M.; Madonna, M.; Murino, T.; Castagna, F. Modelling a Safety Management System Using System Dynamics at the Bhopal Incident. *Appl. Sci.* **2020**, *10*, 903. [CrossRef]
58. Geller, S. Behavioral safety: Meeting the challenge of making a large-scale difference. *Behav. Anal. Today* **2001**, *2*, 64–77. [CrossRef]
59. Paltrinieri, N.; Massaiu, S.; Matteini, A. Human reliability analysis in the petroleum industry. In *Dynamic Risk Analysis in the Chemical and Petroleum Industry*; Butterworth-Heinemann: Oxford, UK, 2016; pp. 181–192. [CrossRef]
60. Arslan, R.; Uzaslan, N.T. Impact of competency-based and target-oriented training on employee performance: A case study. *Ind. High. Educ.* **2017**, *31*, 289–292. [CrossRef]
61. Leveson, N.G. *Engineering a Safer World: Systems Thinking Applied to Safety*; The MIT Press: Cambridge, MA, USA, 2022; Available online: http://sunnyday.mit.edu/workshop2019/STAMP-Intro2019.pdf (accessed on 17 March 2024).
62. Di Nardo, M.; Murino, T. The system dynamics in the human reliability analysis through cognitive reliability and Error Analysis Method: A case study of an LPG Company. *Int. Rev. Civ. Eng. (IRECE)* **2021**, *12*, 56. [CrossRef]
63. Dunlap, S. Behavioral safety. In *Motor Carrier Safety*; CRC Press: Boca Raton, FL, USA, 2020; pp. 231–233. [CrossRef]
64. Pidgeon, N.; O'Leary, M. Organizational Safety Culture: Implications for Aviation Practice. In *Aviation Psychology in Practice*; Gower Technical: Columbus, OH, USA, 2017; pp. 21–43. [CrossRef]
65. Fleming, M.; Guldenmund, F. Organizational culture. In *APA Handbook of Human Systems Integration*; American Psychological Association: Washington, DC, USA, 2015; pp. 589–604. [CrossRef]
66. Leveson, N.G. Applying systems thinking to analyze and learn from events. *Saf. Sci.* **2011**, *49*, 55–64. [CrossRef]
67. ADIPEC. ADIPEC 2024: ADNOC EnergyAI (Nov, 2024). Available online: https://www.adipec.com/energy-ai/ (accessed on 28 November 2024).
68. Hollnagel, E. The four cornerstones of resilience engineering. In *Resilience Engineering Perspectives*; CRC Press: Boca Raton, FL, USA, 2016; Volume 2, pp. 139–156.
69. Fiksel, J. Designing resilient, sustainable systems. *Environ. Sci. Technol.* **2003**, *37*, 5330–5339. [CrossRef]
70. Sienou, A.; Lamine, E.; Pingaud, H. A Method for Integrated Management of Processrisk. *Proc. GRCIS* **2008**, *339*, 17–30.
71. LaPorte, T.R.; Consolini, P.M. Working in practice but not in theory: Theoretical challenges of" high-reliability organizations". *J. Public Adm. Res. Theory J-PART* **1991**, *1*, 19–48.
72. Rasmussen, J. Risk management in a dynamic society: A modelling problem. *Saf. Sci.* **1997**, *27*, 183–213. [CrossRef]
73. Sklet, S. Safety barriers: Definition, classification, and performance. *J. Loss Prev. Process Ind.* **2006**, *19*, 494–506. [CrossRef]
74. Papazoglou, I.A.; Ale, B.J.M. A logical model for quantification of occupational risk. *Reliab. Eng. Syst. Saf.* **2007**, *92*, 785–803. [CrossRef]
75. Li, Y.; Guldenmund, F.W. Safety Management Systems: A broad overview of the literature. *Saf. Sci.* **2018**, *103*, 94–123. [CrossRef]
76. McKinnon, R.C. Management-led Safety Management Systems. In *Risk-Based, Management-Led, Audit-Driven, Safety Management Systems*; CRC Press: Boca Raton, FL, USA, 2016; pp. 55–79. [CrossRef]
77. Mkpat, E.; Reniers, G.; Cozzani, V. Process safety education: A literature review. *J. Loss Prev. Process Ind.* **2018**, *54*, 18–27. [CrossRef]
78. Guldenmund, F.W. The nature of safety culture: A review of theory and research. *Saf. Sci.* **2000**, *34*, 215–257. [CrossRef]
79. O'Rourke, D.; Connolly, S. Just oil? The distribution of environmental and social impacts of oil production and consumption. *Annu. Rev. Environ. Resour.* **2003**, *28*, 587–617. [CrossRef]
80. Nguyen, H.; Uddin, M.Y.S.; Venkatasubramanian, N. Multistage adaptive load balancing for big active data publish subscribe systems. In Proceedings of the 13th ACM International Conference on Distributed and Event-based Systems, Lyon, France, 24–28 June 2019; pp. 43–54.
81. AVEVA. AVEVA Unified Operations Center. Available online: https://www.aveva.com/content/dam/aveva/documents/brochures/Brochure_AVEVA_UnifiedOperationsCenter_24-02.pdf.coredownload.inline.pdf (accessed on 6 December 2024).
82. Antony, J.; Banuelas, R. Key ingredients for the effective implementation of Six sigma program. *Meas. Bus. Excell.* **2002**, *6*, 20–27. [CrossRef]
83. Antony, J.; Fergusson, C. Six sigma in the software industry: Results from a pilot study. *Manag. Audit. J.* **2004**, *19*, 1025–1032. [CrossRef]
84. Lu, Y. Industry 4.0: A survey on technologies, applications and open research issues. *J. Ind. Inf. Integr.* **2017**, *6*, 1–10. [CrossRef]
85. Li, H.; Yu, H.; Cao, N.; Tian, H.; Cheng, S. Applications of artificial intelligence in oil and gas development. *Arch. Comput. Methods Eng.* **2021**, *28*, 937–949. [CrossRef]
86. Echeverria, A.T.; Willnauer, L.; Saunders, S. The House of Integrity: Modern Asset Integrity Management A Process Safety approach. In Proceedings of the 7th Latin American Conference on Process Safety, Lima, Peru, 23–24 August 2016.
87. Boiral, O.; Cayer, M.; Baron, C.M. The action logics of environmental leadership: A developmental perspective. *J. Bus. Ethics* **2009**, *85*, 479–499. [CrossRef]

88. Bryden, R.; Gibson, W. Workforce Involvement in Safety Programme. In Proceedings of the SPE International Conference and Exhibition on Health, Safety, Environment, and Sustainability, Stavanger, Norway, 26–28 June 2000; SPE: Cairo, Egypt, 2000; p. SPE-60998.
89. Zohar, D. Safety climate in industrial organizations: Theoretical and applied implications. *J. Appl. Psychol.* **1980**, *65*, 96. [CrossRef]
90. O'Dea, A.; Flin, R. Site managers and safety leadership in the offshore oil and gas industry. *Saf. Sci.* **2001**, *37*, 39–57. [CrossRef]
91. Jensen, T.; Sandström, J.; Helin, S. One code to rule them all: Management control and individual responsibility in contexts. *Bus. Prof. Ethics J.* **2015**, *34*, 259–290. [CrossRef]
92. Egbeocha, J.O.; Reginald-Ugwuadu, O.G.; Oluchi, E.; Ebisike, R.C.; Obanya, P. Entrenching Process Safety Culture in The Face of Shifting Demography–a key to Sustaining Goal Zero Performance in Well Operations. In Proceedings of the SPE Nigeria Annual International Conference and Exhibition, Lagos, Nigeria, 4–6 August 2015; SPE: Cairo, Egypt, 2015; p. SPE-178345.
93. Faria, E.; Caldeira-Pires, A.; Barreto, C. Social, economic, and institutional configurations of the industrial symbiosis process: A comparative analysis of the literature and a proposed theoretical and analytical framework. *Sustainability* **2021**, *13*, 7123. [CrossRef]
94. Center for Chemical Process Safety (CCPS). *Guidelines for Process Safety Documentation*; American Institute of Chemical Engineers: New York, NY, USA, 2017.
95. American Petroleum Institute (API). *Guidance Document for the Development of a Safety and Environmental Management System for Onshore Oil and Natural Gas Production Operations and Associated Activities*; American Petroleum Institute: Washington, DC, USA, 2016.
96. *1910.119*; Process Safety Management of Highly Hazardous Chemicals. Occupational Safety and Health Administration (OSHA): Washington, DC, USA, 2013.
97. Halim, S.Z.; Mannan, M.S. A journey to excellence in process safety management. *J. Loss Prev. Process Ind.* **2018**, *55*, 71–79. [CrossRef]
98. Zheng, P.; Wang, H.; Sang, Z.; Zhong, R.Y.; Liu, Y.; Liu, C.; Mubarok, K.; Yu, S.; Xu, X. Smart Manufacturing Systems for Industry 4.0: Conceptual Framework, scenarios, and future perspectives. *Front. Mech. Eng.* **2018**, *13*, 137–150. [CrossRef]
99. Aguilera, J.T.; Ruíz, N.L.T. Operational excellence: Concept review and meaning restructuration. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Lisbon, Portugal, 23–25 March 2019; IEOM Society: Southfield, MI, USA, 2019; pp. 678–688.
100. Al-Mazrouie, J.; Bajracharya, A. Study on the Operational Readiness of Mega Construction Project. In Proceedings of the Creative Construction Conference, Budapest, Hungary, 6–9 July 2013; pp. 6–9.
101. Smith, D.J. Quantified reliability centered maintenance. In *Reliability, Maintainability and Risk*; Butterworth-Heinemann: Oxford, UK, 2017; pp. 259–267. [CrossRef]
102. Management of Change (MOC). *Guidelines for Process Hazards Analysis (PHA, HAZOP), Hazards Identification, and Risk Analysis*; CRC Press: Boca Raton, FL, USA, 2018; pp. 197–203. [CrossRef]
103. Guan, J.; Zixuan, Y.; Chan, A.P.; Choi, T.; Yang, Y. Factors affecting learning from incidents: A cross-industry Review. *J. Loss Prev. Process Ind.* **2024**, *89*, 105297. [CrossRef]
104. Begg, C.B.; Berlin, J.A. Publication bias: A problem in interpreting medical data. *J. R. Stat. Society. Ser. A (Stat. Soc.)* **1988**, *151*, 419. [CrossRef]
105. Irandoost, M.A.; Rahmani, A.M.; Setayeshi, S. Mapreduce data skewness handling: A systematic literature review. *Int. J. Parallel Program.* **2019**, *47*, 907–950. [CrossRef]
106. Knottnerus, J.A.; Tugwell, P. Selection-related bias, an ongoing concern in doing and publishing research. *J. Clin. Epidemiol.* **2014**, *67*, 1057–1058. [CrossRef] [PubMed]
107. Smela, B.; Toumi, M.; Świerk, K.; Francois, C.; Biernikiewicz, M.; Clay, E.; Boyer, L. Rapid literature review: Definition and methodology. *J. Mark. Access Health Policy* **2023**, *11*, 2241234. [CrossRef] [PubMed]
108. Xiao, Y.; Watson, M. Guidance on conducting a systematic literature review. *J. Plan. Educ. Res.* **2017**, *39*, 93–112. [CrossRef]
109. Wohlin, C.; Mendes, E.; Felizardo, K.R.; Kalinowski, M. Guidelines for the search strategy to update systematic literature reviews in software engineering. *Inf. Softw. Technol.* **2020**, *127*, 106366. [CrossRef]
110. Carver, J.C.; Hassler, E.; Hernandes, E.; Kraft, N.A. Identifying barriers to the systematic literature review process. In Proceedings of the 2013 ACM/IEEE International Symposium on Empirical Software Engineering and Measurement, Baltimore, MD, USA, 10–11 October 2013; pp. 203–212.
111. Luceri, V.; Pirri, M.; Rodríguez, J.; Appleby, G.; Pavlis, E.C.; Müller, H. Systematic errors in SLR data and their impact on the ILRS products. *J. Geod.* **2019**, *93*, 2357–2366. [CrossRef]
112. Kwarto, F.; Nurafiah, N.; Suharman, H.; Dahlan, M. The potential bias for sustainability reporting of global upstream oil and gas companies: A systematic literature review of the evidence. *Manag. Rev. Q.* **2024**, *74*, 35–64. [CrossRef]
113. Kitchenham, B.; Brereton, P.; Turner, M.; Niazi, M.; Linkman, S.; Pretorius, R.; Budgen, D. The impact of limited search procedures for systematic literature reviews—A participant-observer case study. In Proceedings of the 2009 3rd International Symposium on Empirical Software Engineering and Measurement, Lake Buena Vista, FL, USA, 15–16 October 2009; pp. 336–345.

114. Durach, C.F.; Kembro, J.; Wieland, A. A new paradigm for systematic literature reviews in supply chain management. *J. Supply Chain Manag.* **2017**, *53*, 67–85. [CrossRef]
115. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]