SciEn
Journal of Engineering Advancements Vol. 07(01) 2026, pp 1-15 https://doi.org/10.38032/jea.2026.01.001

Proactive Asset Integrity Management in High-Risk Critical Facilities: A Comprehensive Review and Strategic Framework

Attia Hussien Gomaa

Mechanical Engineering Department, Faculty of Engineering, Shubra, Benha University, Cairo, Egypt.

Received: July 19, 2025, Revised: December 24, 2025, Accepted: December 29, 2025, Available Online: March 02, 2026

ABSTRACT

Asset Integrity Management (AIM) is vital for ensuring the safety, reliability, and sustainability of high-risk industrial assets in sectors such as advanced manufacturing, oil and gas, energy, and petrochemicals. As industrial systems grow increasingly complex, interconnected, and digitally enabled, traditional maintenance approaches often struggle to manage dynamic risks, performance variability, and long-term asset health. This study presents a comprehensive review of AIM methodologies and proposes a proactive, integrated framework that unifies Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM) within a single strategic model. The framework aligns strategic objectives, operational processes, and key performance indicators (KPIs), emphasizing risk mitigation, operational efficiency, workforce capability, and sustainability, while addressing implementation challenges such as leadership engagement, skill gaps, data governance, and digital integration. Conceptually validated across high-reliability industrial contexts, the model enhances Reliability, Availability, Maintainability, and Safety (RAMS) and, by integrating Artificial Intelligence (AI), the Internet of Things (IoT), and Digital Twins, advances Maintenance 4.0—enabling predictive, intelligent, and sustain-able maintenance ecosystems that minimize unplanned downtime, reduce lifecycle costs, and strengthen organizational resilience and long-term value creation.

Keywords: Asset Integrity Management, Risk-Based Inspection, Reliability-Centered Maintenance, Total Productive Maintenance, Operational Excellence, Proactive Maintenance, Sustainable Asset Performance.

Copyright @ All authors

This work is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License.

1 Introduction

In asset-intensive and high-risk sectors—such as energy, petrochemicals, mining, and critical infrastructure—Asset Integrity Management (AIM) has become a strategic necessity for ensuring operational safety, system reliability, environmental compliance, and long-term economic sustainability. AIM provides a structured, lifecycle-oriented approach to managing physical assets, enabling organizations to sustain functionality, prevent critical failures, and enhance overall performance throughout the asset lifespan. By integrating technical, operational, and managerial disciplines, AIM reduces unplanned downtime, mitigates operational risks, and ensures alignment with both regulatory frameworks and stakeholder expectations. The ISO 55000 series reinforces this paradigm, emphasizing the importance of aligning asset management systems with organizational objectives [1],[2].

As illustrated in Fig. 1, AIM is deployed across four interlinked organizational levels: Company, Facility, System, and Asset. At the Company level, strategic asset governance, investment prioritization, and enterprise risk management frameworks are defined. These are cascaded to the Facility level, where site-specific integrity programs, inspection schedules, and performance indicators are implemented. The System level manages the condition and reliability of critical subsystems using monitoring tools and diagnostic analytics. At the Asset level, real-time data from sensors and digital platforms enable predictive maintenance, rapid response, and performance optimization. This vertically integrated structure ensures top-down strategic alignment and bottom-up feedback for continuous improvement and informed decision-making [1].

AIM is inherently proactive and integrated, aiming to optimize Reliability, Availability, Maintainability, and Safety (RAMS) while minimizing lifecycle costs and operational risks. As depicted in Fig. 2, AIM is founded on the seamless integration of seven essential management domains: Financial Management, Inspection Management, Maintenance Management, Failure Management, Work Management, Risk Management, and Safety Management. Together, these domains form a cohesive governance architecture that supports structural and functional integrity, regulatory compliance, and sustained asset performance throughout the lifecycle [1].

AIM also adopts a comprehensive lifecycle perspective, spanning the entire asset journey—from concept and design to operation, maintenance, and decommissioning. As shown in Fig. 3, AIM integrates three core functional domains: Design, Inspection and Maintenance, and Operation. In the design phase, methodologies such as Failure Modes and Effects Analysis (FMEA), Hazard and Operability Studies (HAZOP), Value Engineering (VE), and Design of Experiments (DOE) embed reliability and maintainability into asset architecture from the outset. The inspection and maintenance phase utilizes advanced techniques such as Root Cause Failure Analysis (RCFA), Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), Non-Destructive Testing (NDT), and predictive analytics, often supported by Computerized Maintenance Management Systems (CMMS). During the operational phase, performance is enhanced through frameworks such as Total Productive Maintenance (TPM), Total Quality Management (TQM), Lean Six Sigma, and Health, Safety, and Environment (HSE) programs. Collectively, these practices reinforce RAMS performance

*Corresponding Author Email Address: attia.goma@feng.bu.edu.eg

while ensuring regulatory compliance, operational efficiency, and long-term stakeholder value [1].

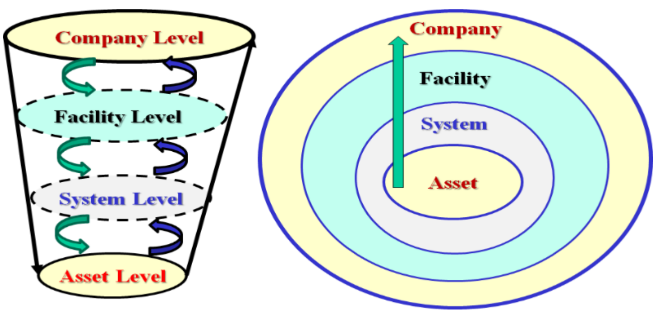
Contemporary AIM emphasizes a proactive maintenance philosophy, moving from reactive and time-based approaches to predictive, risk-informed, and data-driven strategies. Instead of responding to failures, modern AIM anticipates degradation patterns and intervenes based on asset criticality and risk exposure. For low-risk equipment, run-to-failure may be acceptable; however, for high-risk systems, predictive and preventive techniques are essential to avoid catastrophic failure. This strategic shift improves cost-efficiency, resource utilization, and operational resilience [3]-[5].

Furthermore, AIM contributes significantly to sustainable operations, minimizing energy use, emissions, and waste—supporting circular economy goals and environmental stewardship [7]. AIM thus transcends technical boundaries to become a driver of responsible and sustainable industrial performance [4],[5].

Three foundational methodologies—RBI, RCM, and TPM—form the pillars of modern AIM. RBI prioritizes inspection based on failure probability and consequence, optimizing inspection frequency and resource allocation [6],[7]. RCM focuses on identifying functional failures, analyzing root causes, and applying the most effective maintenance strategies to preserve system function [8],[9]. TPM fosters a culture of ownership and proactive maintenance Table 1 compares six prevalent maintenance strategies—Reactive, Time-Based, Condition-Based, Predictive, RCM, and TPM—highlighting their triggers, benefits, limitations, and ideal applications. While reactive and time-based approaches may suit low-risk assets, mission-critical systems demand advanced methodologies.

In response, this study proposes a novel integrated framework for Proactive Asset Integrity Management, combining RBI, RCM, and TPM into a structured and adaptive model. The proposed framework is designed to enhance RAMS outcomes, reduce total lifecycle costs, and drive sustainable operational excellence. By embedding strategic alignment, human-centric practices, and digital intelligence, the framework supports asset-intensive organizations navigating rising complexity, regulatory demands, and performance expectations.

The remainder of this paper is structured as follows: **Section 2** reviews the development and industrial applications of Asset Integrity Management (AIM), Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM). **Section 3** highlights key research gaps and implementation challenges. **Section 4** presents the proposed integrated AIM framework along with its strategic benefits. **Section 5** summarizes the main findings and outlines implications for practice and future research directions.



by involving all employees in preserving equipment health, reducing losses, and improving overall effectiveness [10],[11]. While each of these methodologies offers standalone value, their integration can yield synergistic benefits by holistically addressing the technical, operational, and human aspects of asset performance.

Despite their proven effectiveness, these methodologies are often implemented in silos. Literature reveals a lack of unified, scalable frameworks that integrate RBI, RCM, and TPM in a cohesive AIM strategy. For instance, Shannon et al. (2023) [12] demonstrated TPM-driven improvements in a pharmaceutical facility, while Prasanna et al. (2011) [13] developed a hybrid maintenance model combining RCM, RBI, TPM, and RCFA for pump systems. Yet such applications remain fragmented and context-specific, lacking generalizability.

Moreover, field studies reveal persistent gaps in maintenance governance. Mkandawire et al. (2011) [14] found that over 70% of utilities lacked structured maintenance policies, citing skill gaps, inconsistent implementation, and absence of integrated frameworks. These findings underscore the urgent need for a unified, scalable, and proactive AIM framework that merges RBI, RCM, and TPM into a single coherent model.

To guide this development,

Fig. 1 Asset Integrity Management (AIM) Structure.

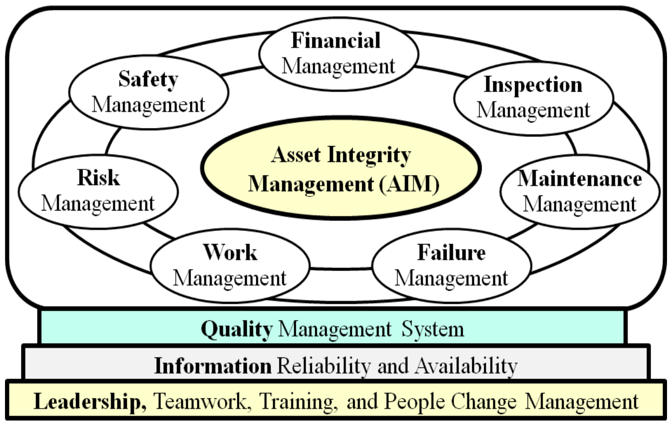


Fig. 2 Integrated Domains of Asset Integrity Management.

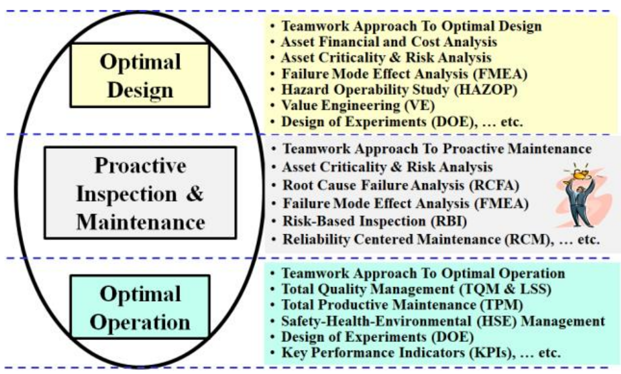


Fig. 3 Main AIM Techniques & Tools.

Table 1 Summary of Maintenance and Inspection Strategies

#	Strategy	Trigger	Advantages	Limitations	Typical Application
1	Reactive Maintenance	Equipment failure	– Simple to implement – No upfront planning	– High downtime and repair costs – Safety risks	Non-critical, low-impact assets
2	Time-Based Maintenance	Fixed intervals	– Easy to schedule – Requires minimal training	– Ignores actual equipment condition – Risk of over-maintenance	Stable, continuously operating assets
3	Condition-Based Maintenance	Real-time condition data	– Improves reliability and availability – Reduces failures	– Requires sensors and skilled staff	Critical assets with variable usage
4	Risk-Based Inspection (RBI)	Risk assessment	– Prioritizes high-risk areas – Optimizes inspection efforts	– Data- and expert-dependent	High-risk, safety-critical systems
5	Reliability-Centered Maintenance (RCM)	Failure modes and criticality	– Focuses on critical maintenance – Enhances reliability and safety	– Data-intensive – Complex to implement	Complex, safety- and mission-critical systems
6	Total Productive Maintenance (TPM)	Employee involvement	– Builds proactive culture – Engages all employees	– Requires strong commitment and training	Manufacturing with continuous improvement focus

2 Literature Review

This study reviews three core proactive maintenance methodologies—Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM)—recognized for their role in enhancing asset integrity, reliability, and operational excellence in high-risk, asset-intensive industries. Together, these approaches form the foundation of modern Asset Integrity Management (AIM) systems, providing complementary strategies for risk prioritization, reliability optimization, and continuous improvement. Despite their widespread adoption, research indicates significant fragmentation and limited integration, which constrains their collective effectiveness.

To address this gap, a Systematic Literature Review (SLR) of publications from 2011–2025 was conducted using Scopus, Web of Science, and ScienceDirect, focusing on the evolution, implementation, and interrelationships of RBI, RCM, and TPM, with particular attention to the enabling roles of digital technologies, leadership engagement, and organizational culture in supporting proactive, data-driven AIM. Individually, RBI prioritizes inspections based on failure probability and consequences; RCM establishes function-based maintenance strategies aligned with system reliability objectives; and TPM fosters operator involvement and continuous improvement, enhancing overall equipment effectiveness (OEE).

While these methodologies are well established, studies such as Prasanna et al. (2011) [13] and Mkandawire et al. (2011) [14] demonstrate that their integration can significantly improve Reliability, Availability, Maintainability, and Safety (RAMS). However, the lack of a scalable, coherent integration framework continues to limit practical implementation. This review thus underscores the need for a comprehensive, proactive AIM framework that combines risk-informed inspections, function-based maintenance planning, and operator-driven improvement initiatives to optimize asset lifecycles, improve maintenance performance, and enable resilient, sustainable, and high-performing industrial operations in the era of digital transformation and smart manufacturing.

2.1 Literature Review on Risk-Based Inspection (RBI)

Risk-Based Inspection (RBI) is a core strategy in Asset Integrity Management (AIM), especially in high-risk, asset-intensive sectors such as oil and gas, energy, and infrastructure. It aims to enhance the safety, reliability, and performance of critical assets by prioritizing inspection and maintenance activities based on the Probability of Failure (PoF) and Consequence of Failure (CoF). This approach enables efficient resource allocation, minimizes unnecessary maintenance, and extends asset life. The American Petroleum Institute (API), through standards such as API 581 (2008), has formalized RBI practices, offering structured methodologies for assessing and managing risks associated with pressure vessels, piping, and other static equipment. These standards have facilitated widespread adoption of RBI in various industries, leading to improved operational safety, cost-effectiveness, and compliance [15].

As shown in Table 2, Recent literature reflects major advancements in RBI, focusing on optimization, digitalization, and customization. Optimization has been a recurring theme, with Javid (2024) [24] introducing a multi-objective genetic algorithm to balance inspection costs and risk reduction, while Javid (2021) [28] employed bi-objective models for inspection planning.

In offshore and subsea applications, RBI methodologies have been adapted to address complex environmental conditions. Almeida de Rezende et al. (2024) [16] integrated fatigue and corrosion models for mooring chain inspections, while Arzaghi et al. (2017) [17] proposed risk-based methods for subsea pipeline maintenance. Song et al. (2021) [18] applied RBI to high-energy piping systems in power plants, demonstrating RBI's relevance in safety-critical systems.

The integration of AI, machine learning, and real-time monitoring—often referred to as RBI 4.0—is gaining momentum. Aditiyawarman et al. (2023) [8] reviewed AI applications for risk analysis in oil and gas, while Zhang et al. (2023) [19] incorporated Condition Monitoring Systems

(CMS) into RBI frameworks to dynamically adjust inspection intervals.

Rachman and Ratnayake (2018) [20] used artificial neural networks to improve screening in hydrocarbon systems, reflecting a broader shift toward predictive and adaptive inspection planning.

RBI has also been tailored to specific asset types and degradation mechanisms. Babaeian et al. (2023) [21] highlighted wall thinning as a major risk factor in gas station components. Eskandarzade et al. (2022) [22] combined RBI with damage progression models for underground pipelines, while Agistina et al. (2021) [15] implemented API 581 in geothermal facilities. These studies underscore RBI's flexibility across industrial domains.

Nevertheless, challenges in practical adoption persist. Abdallah et al. (2022) [7] criticized conventional bridge inspections in the U.S. and advocated for risk-based methods. Kamsu-Foguem (2016) [23] emphasized the need for decision-support systems in sensitive production environments, revealing a gap between theoretical development and field-level implementation.

Overall, Recent research confirms that Risk-Based Inspection (RBI) is highly effective in optimizing asset integrity, minimizing operational risks, and improving inspection scheduling. However, its implementation is frequently isolated from other proactive maintenance strategies, such as Reliability-Centered Maintenance (RCM) and Total Productive Maintenance (TPM). This lack of integration limits the potential for a more cohesive and robust asset management approach. The literature reveals an evident gap in developing a unified framework that synergistically combines RBI with RCM and TPM to enable a more comprehensive, risk-informed, and efficiency-driven maintenance strategy [12],[14]. Addressing this gap necessitates continued research focused on methodological convergence and the evolution of integrated maintenance frameworks aligned with emerging industry demands.

In conclusion, RBI continues to evolve from static, rule-based models toward dynamic, data-driven systems. Its integration with AI, probabilistic models, and real-time data is transforming inspection planning. Yet, to fully realize its potential, RBI must be integrated with complementary methodologies such as Reliability-Centered Maintenance (RCM) and Total Productive Maintenance (TPM), forming a unified framework for proactive, sustainable asset integrity management.

Table 2 Summary of Key Literature on Risk-Based Inspection (RBI).

#	Author(s)	Key Contributions
1	Javid (2024) [24]	Developed a multi-objective RBI framework using genetic algorithms to optimize inspection cost and risk reduction, enabling automated and efficient planning.
2	Almeida de Rezende et al. (2024) [16]	Proposed a reliability-based inspection strategy for offshore mooring chains, integrating fatigue and corrosion models to optimize inspection scheduling.
3	Huang et al. (2023) [25]	Designed an RBI model for pipelines addressing external corrosion and dents, using a Dynamic Bayesian Network (DBN) to improve inspection interval optimization.
4	Babaeian et al. (2023) [21]	Applied a semi-quantitative RBI approach to gas station components, identifying wall thinning as the most critical failure mechanism.
5	Adityawarman et al. (2023) [8]	Reviewed the integration of machine learning in RBI practices for oil and gas, highlighting AI's potential in predictive risk management.
6	Zhang et al. (2023) [19]	Explored the incorporation of Condition Monitoring Systems (CMS) into RBI frameworks, focusing on time-varying CMS performance and lifecycle cost reduction.
7	Eskandarzade et al. (2022) [22]	Proposed an RBI framework for underground pipelines by integrating risk assessments with damage progression modeling.
8	Sözen et al. (2022) [26]	Developed an RBI method for pipelines with internal defects under variable pressure conditions, improving defect prioritization.
9	Abdallah et al. (2022) [7]	Reviewed U.S. bridge inspection practices, emphasizing the need for RBI innovation and integration of modern inspection technologies.
10	Hameed et al. (2021) [27]	Enhanced RBI strategies for offshore pipelines with a focus on corrosion and fatigue-driven failure mechanisms.
11	Javid (2021) [28]	Applied bi-objective optimization to RBI programs to balance safety and economic performance.
12	Yang & Frangopol (2021) [29]	Compared static and adaptive RBI approaches for structural systems, demonstrating the advantages of adaptive strategies in managing deterioration.
13	Song et al. (2021) [18]	Designed an RBI framework for high-energy piping systems in power plants, focused on early failure prediction and prioritization.
14	Agistina et al. (2021) [15]	Implemented API 581-based RBI methodology for geothermal separator machines, identifying critical inspection needs.
15	Abubakirov et al. (2020) [30]	Used dynamic Bayesian networks to optimize inspection intervals in pipeline networks based on evolving risk profiles.
16	Febriyana et al. (2019) [31]	Applied RBI principles for monitoring and managing damage in offshore pipelines.
17	Melo et al. (2019) [32]	Developed a risk-based framework tailored for unpiggable pipelines to guide inspection and maintenance decisions.
18	Rachman & Ratnayake (2018) [20]	Used artificial neural networks to enhance RBI screening processes in hydrocarbon facilities.
19	Arzaghi et al. (2017) [17]	Proposed a dynamic RBI methodology for subsea pipeline maintenance, incorporating evolving risk factors.
20	Kamsu-Foguem (2016) [23]	Improved RBI practices for sensitive production systems in the petroleum sector through knowledge-based decision support.

2.2 Literature Review on Reliability-Centered Maintenance (RCM)

Reliability-Centered Maintenance (RCM) is a structured methodology that prioritizes maintenance activities based on equipment functions, failure modes, and their consequences. By focusing on critical assets, RCM optimizes maintenance strategies to reduce unplanned downtime, extend asset lifespan, and improve resource allocation and decision-making. It also supports safety, regulatory compliance, and continuous improvement by adapting to evolving operational conditions. These attributes enable RCM to align maintenance efforts with organizational objectives, enhancing reliability and mitigating risks. Table 3 summarizes key recent studies illustrating RCM's broad applications.

RCM has gained prominence as an effective tool for optimizing maintenance across diverse sectors such as transportation, manufacturing, power generation, and healthcare. For example, Liu et al. [33] designed advanced RCM strategies for high-speed railways to model asset deterioration and minimize maintenance costs while boosting reliability. Similarly, Ali Ahmed Qaid et al. [34] employed fuzzy logic-based failure mode analysis to develop criticality-driven, data-centric maintenance frameworks for manufacturing equipment.

A prominent trend is the integration of RCM with digital technologies to enhance decision-making and operational efficiency. Introna and Santolamazza [35] investigated the convergence of RCM with Industry 4.0/5.0 technologies, utilizing real-time monitoring and intelligent analytics to elevate asset performance. da Silva et al. [36] introduced the Reliability and Risk-Centered Maintenance (RRCM) framework, combining RCM with Risk-Based Maintenance (RBM) to achieve a balanced optimization of reliability and costs.

RCM's adaptability is evident in its tailored applications across various asset types and industries. Asghari and Jafari [37] demonstrated improved pump reliability and efficiency in water treatment plants, while Sembiring [38] focused on cost-effective maintenance for boiler engines. Jiang et al. [39] enhanced maintenance efficiency in pumped storage plants, and Alrifaey et al. [40] developed hybrid RCM models for the power generation sector.

Beyond industrial domains, RCM has proven beneficial in healthcare and infrastructure. Shamayleh et al. [41] showed that RCM outperforms traditional preventive maintenance in hospital equipment management by reducing downtime and increasing reliability.

Despite documented successes—such as maintenance cost reductions up to 70% [42],[43]—there remain opportunities to refine RCM for non-critical assets and evolving operational environments, as highlighted by Afefy et. al [10].

In conclusion, the literature underscores RCM's vital role in improving maintenance effectiveness, reliability, and cost-efficiency across sectors. Nevertheless, a notable gap persists in integrating RCM with complementary strategies like Risk-Based Inspection (RBI) and Total Productive Maintenance (TPM). Addressing this integration is essential for establishing comprehensive, unified asset management frameworks that maximize performance and sustainability.

Overall, the literature reflects a growing emphasis on integrating RCM with digital tools, risk assessment techniques, and hybrid approaches to develop adaptive, cost-effective maintenance frameworks. This progression aligns with Industry 4.0 trends, supporting predictive and intelligent maintenance. Future research should aim to integrate RCM with complementary methods like Risk-Based Inspection (RBI) and Total Productive Maintenance (TPM) to establish unified asset integrity strategies that maximize reliability, safety, and cost efficiency.

Table 3 Summary of Literature Related to Reliability-Centered Maintenance (RCM).

#	Author(s)	Key Contributions / Applications
1	Liu et al. (2024) [33]	Developed an RCM strategy for high-speed railway facilities by modeling facility deterioration and optimizing maintenance schedules to reduce lifecycle costs.
2	Ali Ahmed Qaid et al. (2024) [34]	Proposed a maintenance framework using Fuzzy-FMECA to evaluate failure modes and recommend criticality-based, data-driven strategies for manufacturing systems.
3	Asghari and Jafari (2024) [37]	Assessed RCM's impact on water treatment plant pumps, reporting increased Mean Time Between Failures (MTBF) and operational performance.
4	Cahyati et al. (2024) [42]	Applied RCM in an industrial plant, achieving a 70% reduction in maintenance costs through systematic reliability analysis.
5	Introna and Santolamazza (2024) [35]	Integrated RCM with digitalization for Industry 4.0/5.0 to enhance asset performance and maintenance intelligence.
6	Jiang et al. (2024) [39]	Optimized RCM for pumped storage power plants, improving efficiency in maintenance planning and resource utilization.
7	Rodríguez-Padial et al. (2024) [44]	Combined RCM with Case-Based Reasoning and fuzzy logic to enhance maintenance planning and risk-based decision-making.
8	Sembiring (2024) [38]	Focused on boiler systems, using RCM to propose strategies that reduce maintenance costs and improve equipment reliability.
9	da Silva et al. (2023) [36]	Introduced Reliability and Risk-Centered Maintenance (RRCM), integrating RCM with Risk-Based Maintenance to optimize cost-reliability trade-offs.
10	Al-Farsi and Syafiie (2023) [45]	Developed a structured 10-step RCM model tailored for maintenance strategy optimization in cement manufacturing.
11	Liu et al. (2023) [33]	Applied RCM to mechanical equipment, improving preventive maintenance practices and minimizing unexpected failures.
12	Enjavimadar and Rastegar (2022) [43]	Implemented RCM in electricity distribution networks, reducing maintenance costs by 7% and enhancing system reliability.
13	Elijaha (2021) [46]	Developed a hybrid RCM-RBM strategy for petrochemical pumps to optimize component-level maintenance.
14	Rosita and Rada (2021) [47]	Applied RCM in a manufacturing environment to reduce downtime and improve system reliability.
15	Alrifaey et al. (2020) [40]	Proposed a hybrid RCM model for power generation, demonstrating improved cost-effectiveness in maintenance practices.
16	Prasetyo and Rosita (2020) [48]	Demonstrated that RCM enhances equipment reliability in manufacturing through systematic maintenance design.
17	Shamayleh et al. (2020) [41]	Highlighted RCM's benefits in hospital medical equipment management compared to traditional preventive maintenance.
18	Afefy et al. (2019) [10]	Improved RCM by including non-critical equipment and optimizing performance metrics, resulting in reduced downtime and maintenance costs.

2.3 Literature Review on Total Productive Maintenance (TPM)

Total Productive Maintenance (TPM) is a comprehensive approach aimed at maximizing Overall Equipment Effectiveness (OEE) by integrating equipment care, operator involvement, and continuous improvement. It combines proactive and predictive maintenance strategies to minimize downtime, enhance reliability, and eliminate waste [12],[49]. TPM emphasizes employee engagement and continuous improvement, driving improvements in product quality, cost reduction, and operational efficiency. Key insights from recent studies across industries are summarized in Table 4.

Biswas (2024) [50] demonstrated that collaboration between multidisciplinary teams and frontline workers in autonomous maintenance led to significant OEE improvements—99% in quality, 49% in availability, and 84% in performance. Additional techniques such as SMED, CMMS, and optimized production planning were recommended to further boost productivity.

In the automotive sector, Jurewicz et al. (2024) [51] showed that integrating Lean Management with TPM reduced downtime and waste, improving equipment availability and efficiency. Mohad et al. (2024) [64] applied Weibull statistical analysis in fertilizer plants to optimize predictive maintenance scheduling and reduce unplanned downtime.

Challenges remain, particularly in emerging economies. Gelaw et al. (2024) [52] reported that Ethiopian manufacturers still rely mainly on breakdown maintenance due to limited management commitment and cultural barriers, highlighting the need for leadership and cultural change.

The fusion of TPM with Industry 4.0 technologies unlocks new opportunities. Khosroniya et al. (2024) [53] found that IoT and big data enhance TPM by optimizing production and enabling adaptive manufacturing. Tortorella et al. (2024) [54] identified operator ownership and autonomous maintenance as critical enablers for successful digital TPM transformation.

TPM also drives sustainability. Samadhiya and Agrawal (2024) [55] found TPM positively impacts economic, environmental, and social sustainability, recommending sustainability-focused training and alignment with Industry 4.0 for competitive advantage.

Beyond manufacturing, TPM proves valuable in logistics and small-scale operations. Meza Jiménez et al. (2024) [56] highlighted benefits in fleet maintenance, while Sangel et al. (2024) [57] improved productivity and reduced waste in machine shops by applying TPM and root cause analysis.

Assessment tools such as AHP aid TPM optimization. Amrina and Firda (2024) [58] identified lubrication, inspection, and cleaning as critical for cement plant maintenance. Wilson et al. (2024) [59] demonstrated that SMEs can implement hybrid TPM models effectively despite limited resources.

In educational environments, Flagg and Amadi (2024) [60] reported enhanced workshop quality through disciplined, planned maintenance. Tailored TPM applications show strong results: Okoro (2024) [61] linked TPM pillars to OEE improvements, Herrera-Barreda (2024) [62] achieved 32% efficiency gains in textile SMEs, and Ardi et al. (2024) [63] increased OEE from 74% to 79% by optimizing key parameters.

In summary, TPM is a versatile, effective strategy for enhancing equipment reliability, productivity, and sustainability. Its integration with Lean and Industry 4.0 technologies amplifies its impact, although success depends on strong management support and cultural adaptation. A notable gap remains in integrating TPM with other maintenance strategies such as Risk-Based Inspection (RBI) and Reliability-Centered Maintenance (RCM). Future research should focus on developing unified frameworks that combine these approaches to meet evolving industrial challenges.

Table 4 Summary of Literature on Total Productive Maintenance (TPM).

#	Author	Key Findings and Applications
1	Biswas (2024) [50]	Team collaboration and autonomous maintenance improved OEE significantly (99% quality, 49% availability, 84% performance); recommended SMED, CMMS, and optimized production planning.
2	Jurewicz et al. (2024) [51]	Integrated Lean and TPM in automotive industry, reducing downtime and waste, boosting equipment performance and productivity.
3	Mohad et al. (2024) [64]	Applied Weibull analysis to enhance TPM planned maintenance, optimizing schedules and reducing downtime in fertilizer plants.
4	Gelaw et al. (2024) [52]	Highlighted early-stage TPM adoption in Ethiopian manufacturing; stressed need for management commitment and cultural change.
5	Khosroniya et al. (2024) [53]	Combined Industry 4.0 (IoT, big data) with TPM, enhancing operational efficiency in industrial parts refurbishment.
6	Samadhiya & Agrawal (2024) [55]	Showed TPM's positive impact on economic, environmental, and social sustainability; emphasized integration with Industry 4.0 and sustainability training.
7	Meza Jiménez et al. (2024) [56]	Applied TPM beyond manufacturing to logistics, improving fleet maintenance, reducing costs, and optimizing warehouse management.
8	Tortorella et al. (2024) [54]	Identified TPM practices critical for Industry 4.0-driven maintenance digitalization, such as operator ownership and autonomous checks.
9	Sangel et al. (2024) [57]	Used TPM tools and root cause analysis in small workshops, enhancing productivity and minimizing waste.
10	Amrina & Firda (2024) [58]	Lubrication prioritized as key TPM factor in cement plants, followed by inspection and cleaning, via AHP assessment.
11	Wilson et al. (2024) [59]	Demonstrated SMEs' ability to implement hybrid TPM systems effectively, improving efficiency despite limited resources.
12	Flagg & Amadi (2024) [60]	Planned maintenance adherence improved quality in technical college electrical workshops; instructors and students aligned on TPM benefits.
13	Okoro (2024) [61]	Positive link between TPM pillars and OEE; recommended customized TPM plans for optimal results.
14	Herrera-Barreda (2024) [62]	Lean and TPM raised efficiency by 32%, cut defects by 29%, and reduced setup times by 27% in textile SMEs, fostering growth and cultural preservation.
15	Ardi et al. (2024) [63]	Increased OEE from 74% to 79% by optimizing engine speed and applying TPM with AHP in finishing operations.
16	Rathi et al. (2023) [65]	Improved manufacturing OEE through focused TPM initiatives.
17	Jurewicz et al. (2024) [51]	New maintenance model in steel plant cuts downtime and waste, increasing productivity by 10% and availability by 14%, approaching global standards.

3 Research Gap Analysis

In asset-intensive and high-risk industries, maintenance practices often suffer from fragmented implementation, leading to inefficiencies, duplicated efforts, and limited coordination. Although Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM) are widely adopted methodologies for enhancing asset performance, they are frequently applied in isolation. Each contributes distinct value: RBI prioritizes interventions based on risk, RCM identifies failure modes and tailors maintenance to asset criticality, and TPM promotes preventive, autonomous practices to improve Overall Equipment Effectiveness (OEE) and reduce downtime.

However, the lack of an integrated framework limits the ability to realize the full benefits of these methodologies. As outlined in Table 5, their siloed application undermines systemic coordination and fails to address the growing complexity of critical facilities. The opportunity lies in developing a unified, proactive Asset Integrity Management (AIM) framework that synergizes RBI's risk prioritization, RCM's failure prevention, and TPM's operational efficiency.

This integration is increasingly necessary under the demands of Industry 4.0, where digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twins, and Big Data Analytics offer advanced capabilities for real-time monitoring, predictive maintenance, and data-driven decision-making. Despite this potential, current AIM approaches rarely cohesively incorporate these enablers.

Key barriers include organizational silos, cultural resistance, technological fragmentation, and the absence of standardized performance indicators to evaluate integrated maintenance systems. Without overcoming these obstacles, efforts to align maintenance with broader strategic goals—such as RAMS, cost-effectiveness, and sustainability—remain limited.

Addressing this gap necessitates the development of a digitally enabled, unified AIM framework that integrates RBI, RCM, and TPM into a comprehensive strategy. Such a framework should incorporate Industry 4.0 technologies and establish clear metrics to assess asset reliability, efficiency, and lifecycle value.

In summary, bridging this research gap represents a vital step toward Maintenance 4.0, enabling organizations to transition from reactive, fragmented practices to intelligent, proactive, and resilient asset management. The proposed integration will provide a robust foundation for both academic exploration and industrial implementation, supporting operational excellence and long-term asset sustainability.

Table 5 Research Gap Analysis.

Dimension	Description
Core Methodologies	- Risk-Based Inspection (RBI): Prioritizes inspection and maintenance based on risk levels to optimize safety and resource utilization. - Reliability-Centered Maintenance (RCM): Identifies failure modes and defines optimal maintenance strategies aligned with asset criticality and function. - Total Productive Maintenance (TPM): Promotes operator-driven, preventive maintenance to maximize OEE, minimize downtime, and sustain asset performance.
Prevailing Limitations	Independent application of RBI, RCM, and TPM leads to siloed planning, redundancy, and limited strategic alignment across maintenance functions.
Identified Research Gap	Absence of an integrated framework that unifies RBI, RCM, and TPM into a cohesive, proactive AIM strategy tailored for complex, asset-intensive environments.
Integration Opportunity	Synergizing RBI's risk prioritization, RCM's failure mitigation, and TPM's operational efficiency can yield a holistic, high-impact approach to asset reliability and lifecycle optimization.
Digital Transformation Enablers	Industry 4.0 technologies (AI, IoT, Digital Twins, Big Data Analytics) offer real-time, predictive insights and decision support but remain underutilized in current AIM integration efforts.
Barriers to Integration	- Organizational silos and resistance to change. - Technological incompatibilities and lack of data interoperability. - Absence of standardized KPIs and integration protocols.
Strategic Imperative	Formulate a unified, digitally enabled AIM framework that seamlessly integrates RBI, RCM, and TPM, supported by advanced technologies and aligned with RAMS, sustainability, and cost-efficiency goals.
Expected Contributions	- Transforms maintenance from reactive to intelligent and predictive. - Enhances asset reliability, availability, and operational resilience. - Establishes a foundational model for Maintenance 4.0 research and implementation.

4 Research Methodology

This study utilizes a structured, three-phase methodology to develop and contextualize a proactive Asset Integrity Management (AIM) framework designed specifically for critical, high-risk industrial facilities. The approach combines an extensive literature review, strategic objective formulation, and implementation analysis to ensure both academic rigor and practical applicability.

Development of an Integrated AIM Framework: A thorough review of existing AIM frameworks and asset management practices was conducted, emphasizing the integration of Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM). The analysis revealed significant gaps caused by fragmented approaches, highlighting the need for a unified and proactive framework. Leveraging best practices and recent technological advancements, the study developed an integrated AIM model aimed at enhancing asset Reliability, Availability, Maintainability, and Safety (RAMS), while embedding sustainability across the asset lifecycle. This framework fosters a shift from reactive to predictive and preventive asset management.

Formulation of Strategic Objectives and Key Performance Indicators (KPIs): Strategic objectives were established to align the AIM framework with key organizational priorities, including risk reduction, operational efficiency, cost control, safety, workforce development, and environmental sustainability. Corresponding KPIs were identified to enable quantitative assessment of progress, incorporating metrics such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), inspection compliance, risk mitigation, and lifecycle cost efficiency. These KPIs support data-driven monitoring and continuous improvement efforts.

Identification of Implementation Challenges and Enabling Strategies: Based on insights from literature and industry experience, common challenges to AIM implementation were identified, including fragmented maintenance processes, limited digital technology adoption, workforce competency gaps, resistance to change, and data quality issues. Enabling strategies were proposed to overcome these barriers, including securing leadership commitment, fostering a culture of continuous improvement, deploying advanced digital tools (e.g., IoT, AI), empowering employees through targeted training, and implementing robust data governance. These strategies promote effective adoption, scalability, and alignment with Industry 4.0 principles.

In conclusion, this methodology delivers a comprehensive, scalable approach to designing an integrated AIM framework that unites RBI, RCM, and TPM into a proactive asset management strategy. By defining clear strategic objectives, measurable KPIs, and practical enabling strategies, the study offers a robust solution to optimize asset performance, improve reliability, mitigate risks, and advance sustainability within complex, high-risk industrial settings. This balanced approach ensures both theoretical soundness and real-world.

4.1 Integrated Framework for Asset Integrity Management (AIM)

This study proposes a unified framework that integrates Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM) to optimize asset integrity management and improve operational performance [14]. The framework commences with RBI, which systematically identifies and prioritizes risks based on asset condition and criticality, enabling efficient resource allocation, minimizing downtime, and preventing costly failures [3].

Building on RBI, RCM develops targeted maintenance plans by analyzing asset functions, failure modes, and their consequences. This structured approach supports cost-effective maintenance decisions that reduce unplanned downtime and extend asset lifecycles [12]. TPM complements these methodologies by fostering a culture of continuous improvement and employee empowerment through autonomous maintenance, defect prevention, and process optimization. This enhances Overall Equipment Effectiveness (OEE) and facilitates early detection of potential failures [49],[55].

Together, these methodologies form a comprehensive, data-driven strategy to enhance Reliability, Availability, Maintainability, and Safety (RAMS) (Prasanna et al., 2011). This integrated approach reduces operational risks, lowers maintenance costs, and boosts productivity, providing a sustainable asset management framework [32]. Fig. 4 and Table 6 outline a structured framework synthesizing RBI, RCM, and TPM into a cohesive and proactive Asset Integrity Management (AIM) strategy. Each methodology contributes unique strengths across the asset lifecycle, and their integration enhances maintenance efficiency, reliability, and sustainability:

Asset Identification and Risk Assessment: Assets are identified and prioritized based on criticality and risk. RBI rigorously evaluates risk levels to concentrate efforts on high-risk assets; RCM analyzes failure modes to identify critical components; TPM engages operators to align maintenance with operational priorities.

Failure Modes and Effects Analysis (FMEA): FMEA guides targeted maintenance planning. RBI applies FMEA to prioritize inspection plans; RCM uses root cause analysis to develop preventive maintenance; TPM incorporates operator insights to address productivity, quality, and safety concerns.

Inspection and Maintenance Strategy Development: Risk and failure analyses translate into actionable inspection and maintenance plans. RBI schedules inspections according to risk; RCM designs maintenance tailored to asset function and importance; TPM emphasizes autonomous and preventive maintenance practices.

Execution of Inspection and Maintenance Actions: Effective execution is vital. RBI focuses inspections on prioritized assets; RCM schedules interventions based on condition monitoring and failure risks; TPM empowers operators to perform daily and scheduled maintenance activities.

Monitoring and Performance Measurement: Continuous data collection facilitates ongoing optimization. RBI updates risk assessments dynamically; RCM refines maintenance schedules based on performance data; TPM tracks OEE to evaluate productivity and guide improvements.

Continuous Improvement: The framework supports adaptive learning. RBI revises inspection protocols based on operational feedback; RCM updates plans incorporating best practices; TPM cultivates a culture of operator-driven continuous improvement.

Training and Collaboration: Sustaining integration demands ongoing education and teamwork. RBI emphasizes risk assessment training; RCM requires expertise in failure analysis and maintenance planning; TPM develops operator skills in autonomous maintenance, fault detection, and teamwork, promoting organizational alignment.

By combining RBI, RCM, and TPM within a unified, data-driven system, this framework significantly enhances asset reliability, availability, and safety while optimizing maintenance costs and resource utilization. The integration of Industry 4.0 technologies—such as IoT, Artificial Intelligence (AI), and Digital Twins—further enables real-time monitoring, predictive analytics, and informed decision-making, driving continuous operational excellence. This holistic framework strengthens organizational resilience and aligns maintenance efforts with strategic business objectives, empowering industries to effectively manage complex, high-risk, asset-intensive environments.

The framework's success is measurable through key performance indicators (KPIs) including reductions in unplanned downtime, improvements in OEE, cost savings (labor, parts, downtime), optimized resource allocation, and asset lifespan extension—quantified by metrics such as Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) that reflect RCM and TPM effectiveness [37].

The primary benefits of the integrated framework include a holistic maintenance approach that combines RBI's risk prioritization, RCM's reliability focus, and TPM's proactive maintenance culture to optimize asset performance by addressing critical failure points and reducing downtime [46]. It also drives cost efficiency by prioritizing maintenance resources on high-risk assets, minimizing unnecessary interventions, and enhancing safety by proactively identifying failure modes and embedding safety protocols into maintenance activities.

Furthermore, the framework encourages continuous process and equipment optimization by leveraging real-time performance data, emerging risks, and technological advancements to evolve maintenance strategies [12].

For successful implementation, organizations must integrate data systems, invest in comprehensive training, and foster cross-functional collaboration [49]. Fragmented data systems can impede integration, whereas unified platforms that consolidate data from RBI, RCM, and TPM enable seamless access to real-time information and support data-driven decision-making. Shifting from reactive to proactive maintenance may encounter resistance, which can be overcome through strong leadership, transparent communication, and ongoing employee engagement [11]. Establishing dedicated teams to oversee the integration ensures alignment with organizational goals and efficient coordination across departments. Given the resource demands of integration, phased implementation facilitates manageable adoption and efficient use of skilled personnel.

The effective deployment of advanced technologies—including predictive analytics, Digital Twins, IoT, and AI—is crucial. These tools provide real-time asset monitoring and actionable insights that guide ongoing optimization of maintenance strategies [66]-[68].

In conclusion, this research presents a robust, integrated framework combining RBI, RCM, and TPM to optimize asset management and enhance operational efficiency. By harnessing Industry 4.0 technologies, addressing implementation challenges, and monitoring success through clear KPIs, this approach enables organizations to reduce risks, improve asset performance, and achieve sustainable competitiveness in an increasingly complex industrial landscape.

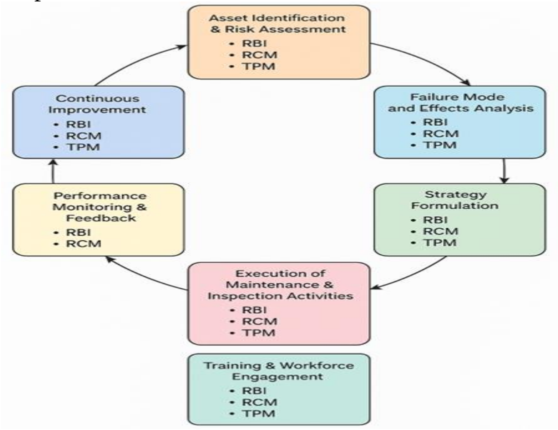


Fig. 4 Integrated Proactive AIM Framework.

Table 6 Integrated AIM Framework - Strategic Alignment of RBI, RCM, and TPM Dimensions.

#	Dimension	RBI	RCM	TPM
1	Asset Identification & Risk Assessment	Systematically prioritizes assets based on risk matrices, focusing on the likelihood and consequence of failure to optimize inspection resources.	Identifies critical assets through functional failure analysis and assessment of system-level consequences.	Engages frontline operators in identifying essential equipment aligned with operational goals and production priorities.
2	Failure Modes and Effects Analysis (FMEA)	Directs inspection strategies toward high-risk failure modes with potential safety, environmental, or economic impact.	Determines root causes of functional failures and develops asset-specific maintenance strategies.	Detects and addresses recurring equipment issues impacting reliability, quality, and throughput using experiential knowledge.
3	Strategy Formulation	Establishes inspection plans and frequencies based on risk profiles, degradation mechanisms, and regulatory requirements.	Defines preventive, predictive, and failure-finding tasks based on asset function, failure effects, and risk tolerance.	Develops standardized maintenance routines, including autonomous maintenance, lubrications, and early equipment management.
4	Execution of Maintenance Activities	Implements prioritized inspections using advanced non-destructive testing (NDT), sensors, and condition-monitoring tools.	Executes condition-based and reliability-focused maintenance actions supported by technical diagnostics.	Conducts routine operator-led maintenance and planned interventions supported by team-based problem solving.
5	Performance Monitoring & Feedback	Analyzes inspection data to reassess risk levels and optimize inspection intervals and techniques.	Tracks key reliability metrics (e.g., MTBF, MTTR) and refines maintenance strategies accordingly.	Monitors Overall Equipment Effectiveness (OEE), identifies productivity losses, and promotes real-time problem resolution.
6	Continuous Improvement	Continuously refines inspection strategies through data analytics, root cause analysis, and risk reassessment.	Enhances maintenance programs using historical failure data, performance trends, and stakeholder feedback.	Fosters a culture of ongoing improvement through Kaizen events, small group activities, and team collaboration.
7	Training & Workforce Engagement	Builds technical capacity in risk assessment, inspection planning, and compliance through structured training programs.	Enhances staff expertise in systems thinking, failure analysis, and maintenance strategy development.	Empowers operators through skills development in early fault detection, basic care, and ownership of equipment reliability.

4.2 Formulation of Strategic Objectives and Key Performance Indicators (KPIs)

Strategic objectives were established to align closely with organizational goals focused on risk mitigation, operational efficiency, and sustainable asset management. Corresponding Key Performance Indicators (KPIs) were selected to quantitatively evaluate the effectiveness of the AIM framework. Table 7 presents a clear overview of these objectives and KPIs, supporting a balanced approach to managing asset performance, safety, costs, workforce development, and environmental responsibility.

Maximize Asset Reliability and Availability: This objective aims to ensure assets operate consistently with minimal downtime. KPIs such as Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR) track failure frequency and repair speed. Overall Equipment Effectiveness (OEE) combines availability, performance, and quality metrics, while indicators like Failure Detection Lead Time and Predictive Maintenance Accuracy assess the effectiveness of AI-driven failure prediction.

Optimize Maintenance Costs and Resource Utilization: This objective focuses on controlling maintenance expenses and improving resource efficiency. Metrics include Maintenance Cost as a Percentage of Revenue and Reduction in Unplanned Downtime. The level of IoT-enabled condition monitoring adoption indicates progress in digitalization, and AI-optimized spare parts inventory reduction quantifies cost savings from predictive analytics.

Enhance Safety and Regulatory Compliance: Ensuring workplace safety and regulatory adherence is central to this objective. Number of Safety Incidents measures safety performance, while Compliance Audit Scores track conformity to standards, helping maintain legal and operational integrity.

Improve Operational Efficiency: This objective measures the effectiveness and timeliness of maintenance activities through KPIs such as Maintenance Work Order Completion Rate and Mean Time Between Maintenance (MTBM), balancing maintenance needs with operational continuity.

Foster Workforce Competence and Engagement: Focused on developing skilled, engaged personnel, this objective uses Training Hours per Employee to gauge investment in employee development, and Operator-Initiated Maintenance Requests to reflect proactive operator involvement and ownership.

Support Sustainability and Environmental Goals: Aligned with sustainability commitments, this objective tracks Energy Consumption per Asset and the Percentage of Eco-Friendly Maintenance Activities, promoting environmentally responsible practices to reduce environmental impact.

In conclusion, the defined strategic objectives and KPIs provide a comprehensive framework for effective Asset Integrity Management. By addressing reliability, cost-efficiency, safety, operational performance, workforce engagement, and sustainability, this approach supports data-driven decision-making and continuous improvement, ensuring resilient and sustainable asset operations in line with Industry 4.0 principles.

Table 7 Strategic Objectives & KPIs for AIM Implementation.

#	Strategic Objective	Key Performance Indicators (KPIs)	Formula / Measurement	Purpose / Impact
1	Maximize Asset Reliability & Availability	- Mean Time Between Failures (MTBF)	Total Operating Time ÷ Number of Failures	Measures asset reliability
		- Mean Time to Repair (MTTR)	Total Downtime ÷ Number of Repairs	Evaluates repair efficiency
		- Overall Equipment Effectiveness (OEE)	Availability × Performance × Quality	Assesses overall equipment productivity
		- Failure Detection Lead Time (FDLT) (%)	(Time Before AI Prediction ÷ Time Before Actual Failure) × 100	Measures lead time advantage of predictive maintenance
		- Predictive Maintenance Accuracy (%)	(Correct AI Predictions ÷ Total Predictions) × 100	Assesses accuracy of predictive maintenance AI
2	Optimize Maintenance Costs & Resource Utilization	- Maintenance Cost as % of Revenue	(Total Maintenance Cost ÷ Total Revenue) × 100	Tracks maintenance cost efficiency
		- Reduction in Unplanned Downtime (%)	((Previous Downtime − Current Downtime) ÷ Previous Downtime) × 100	Measures reduction in unplanned downtime
		- IoT-Enabled Condition Monitoring Adoption (%)	(Number of IoT-Monitored Assets ÷ Total Assets) × 100	Indicates extent of digital condition monitoring
		- AI-Optimized Spare Parts Inventory Reduction (%)	((Previous Inventory Cost − Current Inventory Cost) ÷ Previous Inventory Cost) × 100	Tracks optimization of spare parts inventory
3	Enhance Safety and Regulatory Compliance	- Number of Safety Incidents	Total recorded safety incidents	Monitors safety performance
		- Compliance Audit Score	(Number of Compliant Items ÷ Total Audit Items) × 100	Measures adherence to regulations and standards
4	Improve Operational Efficiency	- Maintenance Work Order Completion Rate (%)	(Completed Work Orders ÷ Scheduled Work Orders) × 100	Tracks effectiveness of maintenance execution
		- Mean Time Between Maintenance (MTBM)	Total Operating Time ÷ Number of Maintenance Actions	Measures average interval between maintenance actions
5	Foster Workforce Competence & Engagement	- Training Hours per Employee	Total Training Hours Delivered ÷ Number of Maintenance Personnel	Measures investment in workforce development
		- Operator-Initiated Maintenance Requests	Number of Maintenance Requests Initiated by Operators	Indicates operator engagement and proactivity
6	Support Sustainability & Environmental Goals	- Energy Consumption per Asset	Total Energy Consumed ÷ Number of Assets	Monitors energy efficiency and consumption
		- Percentage of Eco-Friendly Maintenance Activities	(Eco-Friendly Maintenance Actions ÷ Total Maintenance Actions) × 100	Tracks adoption of sustainable maintenance practices

4.3 Identification of AIM Implementation Challenges and Enabling Strategies

Insights from literature and industry practice reveal several common challenges that can hinder the successful implementation of an Asset Integrity Management (AIM) framework. These include fragmented maintenance systems, limited digital adoption, organizational resistance to change, and skill gaps among the workforce. Table 8 summarizes these challenges along with strategic enabling measures designed to effectively address them.

Leadership & Culture: Strong leadership commitment and a supportive organizational culture are critical for AIM success. Challenges such as insufficient leadership involvement and cultural resistance can impede progress. To overcome these barriers, organizations should align AIM initiatives with strategic objectives, foster accountability, and promote a culture of continuous improvement through clear communication and visible leadership support.

Workforce Competency: A skilled and adaptable workforce is essential for adopting new AIM practices and digital tools. Skill shortages and resistance to change are common obstacles. Providing comprehensive training, continuous professional development, and proactive change management empowers employees and encourages buy-in for new approaches.

Process Alignment: Fragmented and inconsistent maintenance and inspection processes reduce efficiency and complicate AIM integration. Standardizing procedures and fostering cross-functional collaboration enable smooth integration of Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM), enhancing consistency and decision-making quality.

Resource Constraints: Limited budgets, personnel shortages, and competing priorities often restrict AIM efforts. Prioritizing initiatives based on risk and impact, combined with demonstrating early successes through pilot projects, helps secure ongoing investment and stakeholder support.

Data Quality & Governance: Reliable, accurate data is fundamental for effective AIM, especially for predictive analytics. Challenges such as inconsistent data collection and weak governance undermine data integrity. Establishing strong data management policies, standardizing processes, and implementing validation controls improve data quality and analytical reliability.

Change Management: Resistance to new processes and technologies can slow AIM adoption. Effective change management involves transparent communication, active stakeholder engagement, phased rollouts, and feedback mechanisms to foster acceptance and facilitate smooth transitions.

Digital Integration: Integrating advanced digital technologies with legacy systems can be complex, limiting real-time monitoring and analytics capabilities. Investing in interoperable, scalable platforms and adopting open standards facilitate seamless integration of IoT, AI, and cloud technologies, enabling enhanced asset visibility and predictive maintenance aligned with Industry 4.0 principles.

In conclusion, successfully implementing an AIM framework requires addressing diverse challenges spanning leadership, workforce capabilities, process harmonization, resource allocation, data governance, change management, and digital technology integration. By applying targeted enabling strategies—such as strong leadership engagement, workforce training, standardized processes, robust data management, effective change initiatives, and scalable digital solutions—organizations can overcome these barriers. This integrated approach not only supports effective AIM adoption but also drives improved asset reliability, operational efficiency, and sustainability, positioning critical facilities to thrive in today's increasingly complex and digitized industrial environment.

Table 8 AIM Implementation Challenges and Enabling Strategies.

#	Category	Challenge	Enabling Strategy
1	Leadership & Culture	Lack of leadership support and cultural resistance impede AIM adoption.	Secure executive sponsorship and cultivate a culture of accountability and continuous improvement.
2	Workforce Competency	Skill gaps and resistance hinder effective AIM implementation.	Provide targeted technical and digital training; engage employees early and encourage participation.
3	Process Alignment	Fragmented maintenance and inspection processes reduce efficiency.	Standardize and integrate RBI, RCM, and TPM processes through cross-functional collaboration.
4	Resource Constraints	Limited budgets, staffing, and time restrict implementation.	Prioritize critical assets, demonstrate ROI with pilots, and ensure sustained funding.
5	Data Quality & Governance	Poor data quality and weak governance undermine decisions.	Establish robust data governance, implement validation procedures, and leverage analytics tools.
6	Change Management	Resistance to change and new technology delays adoption.	Engage stakeholders early, communicate benefits clearly, and apply phased implementation with feedback.
7	Digital Integration	Legacy systems and incompatible technologies limit real-time insights.	Invest in interoperable, scalable platforms using open standards for seamless digital integration.

5 Conclusion and Future Work

This study provides a comprehensive review of contemporary Asset Integrity Management (AIM) methodologies and proposes a proactive, integrated framework that synthesizes Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM). The framework establishes a coherent alignment between key performance indicators (KPIs) and organizational objectives aimed at risk mitigation, operational excellence, workforce capability development, and sustainability.

Recognizing the limitations of traditional maintenance practices in increasingly complex and digitally interconnected industrial systems, the study identifies several key implementation challenges, including limited leadership engagement, workforce skill gaps, fragmented processes, and barriers to digital integration. To address these, it proposes enabling strategies emphasizing leadership commitment, competency development, process standardization, data governance, and the adoption of Industry 4.0 technologies.

The proposed framework offers a scalable and adaptable model for enhancing asset integrity, performance, and resilience. Each pillar contributes unique value: RBI ensures risk-informed inspection prioritization; RCM aligns maintenance strategies with asset function and criticality; and TPM fosters a culture of ownership and continuous improvement. Designed for digital compatibility, the framework supports reductions in unplanned downtime, lifecycle costs, and risk exposure, while enhancing organizational agility and system sustainability.

Importantly, this integrated model could significantly advance research and practice in integrated maintenance and Maintenance 4.0. By bridging classical reliability methodologies with digital transformation enablers—such as AI, IoT, and Digital Twins—the framework provides a foundation for intelligent, data-driven maintenance ecosystems. It promotes cross-disciplinary collaboration and supports the evolution toward autonomous, predictive, and sustainable asset management systems.

By addressing a critical gap in AIM theory and practice, the study contributes to strengthening Reliability, Availability, Maintainability, and Safety (RAMS) performance across asset-intensive sectors. Future research should focus on empirical validation, quantitative benchmarking, and cross-industry application to ensure contextual adaptability and to refine its contribution to proactive and resilient industrial systems.

Theoretical Implications: The study advances AIM theory by conceptualizing a unified, systems-oriented framework that integrates RBI, RCM, and TPM within the context of Maintenance 4.0. It contributes to the evolving discourse on digitally enabled, proactive asset management and provides a theoretical foundation for future interdisciplinary research in engineering, operations, and systems management.

Practical Implications: For practitioners, the framework serves as a strategic roadmap for implementing holistic AIM practices. It enables cross-functional integration, supports data-driven decision-making, and aligns maintenance strategies with business objectives—thereby enhancing asset reliability, operational continuity, and cost efficiency in complex industrial environments.

Managerial Implications: From a leadership perspective, the framework underscores the importance of executive sponsorship, workforce development, and digital capability building in achieving AIM excellence. It equips managers with actionable insights to embed continuous improvement, prioritize risk-based strategies, and transform maintenance from a reactive to a proactive, value-creating function.

Study Limitations: Although conceptually robust, this study is primarily based on a structured literature review and theoretical synthesis. Its generalizability may be constrained by the absence of large-scale empirical validation across multiple sectors. Moreover, contextual variables—such as regulatory environments, organizational culture, and digital maturity—were not deeply examined and should be explored in future work.

Future Research Directions: Future research should extend and validate the proposed AIM framework across theoretical, technological, and practical dimensions.

Empirical Validation: Conduct longitudinal and cross-sector studies to assess the framework's effectiveness, scalability, and long-term impact on asset reliability, resilience, and value creation. Comparative benchmarking with conventional maintenance strategies can highlight its relative advantages.

Technological Integration: Explore the integration of AI, Digital Twins, IoT, and Blockchain to enhance data interoperability, predictive intelligence, and autonomous decision-making within AIM systems, enabling self-optimizing and adaptive maintenance ecosystems.

Implementation Tools: Develop sector-specific implementation roadmaps and AIM maturity assessment models to guide organizations through structured stages of digital transformation, ensuring alignment between technical capabilities, human competencies, and strategic objectives.

Organizational and Policy Dimensions: Investigate how leadership commitment, culture, change management, and policy frameworks influence AIM adoption, sustainability, and systemic improvement.

Future Paradigms: Examine the framework's evolution in the context of Industry 5.0 and Industry 6.0, focusing on human-centricity, ethical intelligence, circularity, and resilience. By integrating cognitive, emotional, and regenerative technologies, AIM can progress toward conscious, adaptive, and sustainable maintenance ecosystems that align technological innovation with societal and environmental well-being.

Acknowledgements

None to declare.

Author Contributions

A. H. Gomaa: Conceptualization, methodology, formal analysis, investigation, data curation, visualization, and writing (original draft and review).

Conflicts of Interest

The author declares no conflicts of interest.

Funding Information

This research received no external funding.

Generative Artificial Intelligence Statement

ChatGPT was used solely for language refinement. No generative AI was employed in data analysis, interpretation, or content generation. The author retains full responsibility for the manuscript.

Data Availability Statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Gomaa, A.H., 2025. Asset Management Excellence: A Roadmap for Integrating Lean Six Sigma and ISO 55001 to Achieve Operational Excellence. Intelligent and Sustainable Manufacturing, 2025, 2(2), pp. 1-19.

[2] Odili, P.O., Daudu, C.D., Adefemi, A., Ekemezie, I.O. and Usiagu, G.S., 2024. Operational readiness and assurance (OR&A) in asset integrity: strategies for excellence in facility management. Engineering Science & Technology Journal, 5(2), pp.581-596.

[3] Gomaa, A.H., 2023. Maintenance process improvement framework using lean six sigma: A case study. International Journal of Business & Administrative Studies, 9(1), pp. 1-25.

[4] Gomaa, A.H., 2024a. Enhancing proactive maintenance of critical equipment by integrating digital twins and lean six sigma approaches. International Journal of Modern Studies in Mechanical Engineering (IJMSME) Volume 10, Issue 1, 2024, PP 20-35.

[5] Gomaa, A.H., 2024b. Improving shutdown maintenance management performance using lean six sigma approach: A case study. International Journal of Applied and Physical Sciences, IJAPS, 10(1), pp.1-14.

[6] Samadhiya, A. and Agrawal, R., 2024. Total productive maintenance and sustainability performance: resource-

based view perspective. Benchmarking: An International Journal, 31(7), pp.2177-2196.

[7] Abdallah, A.M., Atadero, R.A. and Ozbek, M.E., 2022. A state-of-the-art review of bridge inspection planning: current situation and future needs. Journal of Bridge Engineering, 27(2), p.03121001.

[8] Aditiyawarman, T., Kaban, A.P.S. and Soedarsono, J.W., 2023. A recent review of risk-based inspection development to support service excellence in the oil and gas industry: An Artificial Intelligence Perspective. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering, 9(1), p.010801.

[9] Ben-Daya, M., 2000. You may need RCM to enhance TPM implementation. *Journal of Quality in Maintenance Engineering*, *6*(2), pp.82-85.

[10] Afefy, I.H., Mohib, A., El-Kamash, A.M. and Mahmoud, M.A., 2019. A new framework of reliability-centered maintenance. Jordan Journal of Mechanical & Industrial Engineering, 13(3).

[11] Adesta, E.Y., Prabowo, H.A. and Agusman, D., 2018. Evaluating 8 pillars of Total Productive Maintenance (TPM) implementation and their contribution to manufacturing performance. In *IOP conference series: materials science and engineering* (Vol. 290, No. 1, p. 012024). IOP Publishing.

[12] Shannon, N., Trubetskaya, A., Iqbal, J. and McDermott, O., 2023. A total productive maintenance & reliability framework for an active pharmaceutical ingredient plant utilising design for Lean Six Sigma. *Heliyon*, *9*(10).

[13] Prasanna, N.K.K., Akula, S. and Desai, T.N., 2011, December. Integration of maintenance strategies for improved asset reliability and availability. In *2011 IEEE International Conference on Industrial Engineering and Engineering Management* (pp. 1514-1518). IEEE.

[14] Mkandawire, B.O.B., Ijumba, N.M. and Whitehead, H., 2011. Application of maintenance tools and strategies in integrated risk management of critical physical assets. *International Journal of Agile Systems and Management*, *4*(3), pp.261-279.

[15] Agistina, A., Budiasih, E. and Pramoso, A., 2021, February. Determination of risk Level, remaining life prediction, and risk-based inspection planning based on API 581. In IOP Conference Series: Materials Science and Engineering (Vol. 1034, No. 1, p. 012116). IOP Publishing.

[16] Huang de Rezende, F., Videiro, P.M., Volnei Sudati Sagrilo, L., de Oliveira, M.C. and dos Santos, G.Y.M., 2024, June. A tool for reliability-based inspection planning of mooring chains. In International Conference on Offshore Mechanics and Arctic Engineering (Vol. 87790, p. V002T02A036). American Society of Mechanical Engineers.

[17] Arzaghi, E., Abaei, M.M., Abbassi, R., Garaniya, V., Chin, C. and Khan, F., 2017. Risk-based maintenance planning of subsea pipelines through fatigue crack growth monitoring. Engineering Failure Analysis, 79, pp.928-939.

[18] Song, J.S., Lok, V., Yoon, K.B., Ma, Y.W. and Kong, B.O., 2021. Quantitative risk-based inspection approach for high-energy piping using a probability distribution function and modification factor. International Journal of Pressure Vessels and Piping, 189, p.104281.

[19] Zhang, W.H., Qin, J., Lu, D.G., Liu, M. and Faber, M.H., 2023. Quantification of the value of condition monitoring system with time-varying monitoring performance in the context of risk-based inspection. Reliability Engineering & System Safety, 231, p.108993.

[20] Rachman, A. and Ratnayake, R.C., 2018, June. Artificial neural network model for risk-based inspection screening assessment of oil and gas production system. In ISOPE International Ocean and Polar Engineering Conference (pp. ISOPE-I). ISOPE.

[21] Babaeian, A., Eslami, A., Ashrafizadeh, F., Golozar, M.A., Samadzadeh, M. and Abbasian, F., 2023. Risk-based inspection (RBI) of a gas pressure reduction station. Journal of Loss Prevention in the Process Industries, 84, p.105100.

[22] Eskandarzade, M., Shahrivar, R., Ratnayake, R.C. and Bukhari, U.N., 2022. An optimal approach for semiquantitative risk-based inspection of pipelines. Journal of Pipeline Systems Engineering and Practice, 13(3), p.04022017.

[23] Kamsu-Foguem, B., 2016. Information structuring and risk-based inspection for the marine oil pipelines. Applied Ocean Research, 56, pp.132-142.

[24] Javid, Y., 2024. Efficient risk-based inspection framework: Balancing safety and budgetary constraints. Reliability Engineering & System Safety, 253, p.110519.

[25] Huang, Y., Qin, G. and Yang, M., 2023. A risk-based approach to inspection planning for pipelines considering the coupling effect of corrosion and dents. Process Safety and Environmental Protection, 180, pp.588-600.

[26] Sözen, L., Yurdakul, M. and Ic, Y.T., 2022. Risk-based inspection planning for internal surface defected oil pipelines exposed to fatigue. International Journal of Pressure Vessels and Piping, 200, p.104804.

[27] Hameed, H., Bai, Y. and Ali, L., 2021. A risk-based inspection planning methodology for integrity management of subsea oil and gas pipelines. Ships and offshore structures, 16(7), pp.687-699.

[28] Javid, Y.J.P.S., 2021. A bi-objective mathematical model to determine risk-based inspection programs. Process Safety and Environmental Protection, 146, pp.893-904.

[29] Yang, D.Y. and Frangopol, D.M., 2021. Risk-based inspection planning of deteriorating structures. Structure and Infrastructure Engineering, 18(1), pp.109-128.

[30] Abubakirov, R., Yang, M. and Khakzad, N., 2020. A risk-based approach to determination of optimal inspection intervals for buried oil pipelines. Process Safety and Environmental Protection, 134, pp.95-107.

[31] Febriyana, P., Haryadi, G.D., Widodo, A., Tauviqirrahman, M., Suprihanto, A., Adigama, A.S., Susilo, D.D. and Kim, S.J., 2019, April. Evaluation for detecting and monitoring of offshore pipeline damage based on risk-based inspection method. In AIP Conference Proceedings (Vol. 2097, No. 1). AIP Publishing.

[32] Melo, C., Dann, M.R., Hugo, R.J. and Janeta, A., 2019. A framework for risk-based integrity assessment of unpiggable pipelines subject to internal corrosion. Journal of Pressure Vessel Technology, 141(2), p.021702.

[33] Liu, G., Liu, L., Li, Q., Wang, Q. and Zhang, H., 2024, August. Reliability-Centered Maintenance Scheduling Optimization for High-Speed Railway Facilities with Multi-level Tasks. In *International Conference on Traffic*

and Transportation Studies (pp. 51-60). Singapore: Springer Nature Singapore.

[34] Ali Ahmed Qaid, A., Ahmad, R., Mustafa, S.A. and Mohammed, B.A., 2024. A systematic reliability-centred maintenance framework with fuzzy computational integration–A case study of manufacturing process machinery. Journal of Quality in Maintenance Engineering, 30(2), pp.456-492.

[35] Introna, V. and Santolamazza, A., 2024. Strategic maintenance planning in the digital era: A hybrid approach merging Reliability-Centered Maintenance with digitalization opportunities. Operations Management Research, pp.1-24.

[36] da Silva, R.F., Melani, A.H.D.A., Michalski, M.A.D.C. and de Souza, G.F.M., 2023. Reliability and Risk Centered Maintenance: A novel method for supporting maintenance management. *Applied Sciences*, *13*(19), p.10605.

[37] Asghari, A. and Jafari, S.M., 2024. Investigating the Influence of reliability centered maintenance on water treatment plant pumps (Case study: Guilan water treatment plant). Journal of Water and Wastewater; Ab va Fazilab (in persian), 35(1), pp.86-102.

[38] Sembiring, A.C., 2024. Analysis of boiler machine maintenance using the reliability-centered maintenance method. JKIE (Journal Knowledge Industrial Engineering), 11(1), pp.1-8.

[39] Jiang, Q., Li, X., Yang, L., Ma, Y. and Li, H., 2024. Innovation and application of reliability-centered maintenance technology for pumped storage power plant. In Journal of Physics: Conference Series (Vol. 2694, No. 1, p. 012014). IOP Publishing.

[40] Alrifaey, M., Sai Hong, T., As' arry, A., Elianddy Supeni, E. and Ang, C.K., 2020. Optimization and selection of maintenance policies in an electrical gas turbine generator based on the hybrid reliability-centered maintenance (RCM) model. Processes, 8(6), p.670.

[41] Shamayleh, A., Awad, M. and Abdulla, A.O., 2020. Criticality-based reliability-centered maintenance for healthcare. Journal of Quality in Maintenance Engineering, 26(2), pp.311-334.

[42] Cahyati, S., Puspa, S.D., Himawan, R., Agtirey, N.R. and Leo, J.A., 2024. Optimization of preventive maintenance on critical machines at the Sabiz 1 plant using reliability-centered maintenance method. Sinergi (Indonesia), 28(2), pp.355-368.

[43] Enjavimadar, M. and Rastegar, M., 2022. Optimal reliability-centered maintenance strategy based on the failure modes and effect analysis in power distribution systems. Electric Power Systems Research, 203, p.107647.

[44] Rodríguez-Padial, N., Marín, M.M. and Domingo, R., 2024. Improvement of industrial maintenance plans through assistance-driven reliability-centered maintenance and case-based reasoning Design. Electronics, 13(3), p.639.

[45] Al-Farsi, N. and Syafiie, S., 2023, April. Reliability centered maintenance application for the development of maintenance strategy for a chemical plant. In International Conference on Mathematical and Statistical Physics, Computational Science, Education, and Communication (ICMSCE 2022) (Vol. 12616, pp. 211-214). SPIE.

[46] Elijaha, P.T., 2021. Modeling effective maintenance strategy using reliability centered maintenance with risk maintenance. FUPRE Journal of Scientific and Industrial Research (FJSIR), 5(1), pp.38-56.

[47] Rosita, K.K.M. and Rada, M.V., 2021, April. Equipment reliability optimization using predictive reliability centered maintenance. In 2021 IEEE 8th International Conference on Industrial Engineering and Applications (ICIEA) (pp. 348-354). IEEE.

[48] Prasetyo, Y.T. and Rosita, K.K.M., 2020, September. Equipment reliability optimization using predictive reliability centered maintenance: a case-study illustration and comprehensive literature review. In *2020 7th International Conference on Frontiers of Industrial Engineering (ICFIE)* (pp. 93-97). IEEE.

[49] Samsudin, S., 2019. The Moderating Effects of Leadership Roles between Total Productive Maintenance (TPM) Practices and Organisation Performance in Power Generation Industry, Doctoral.

[50] Biswas, J., 2024. Total productive maintenance: an in-depth review with a focus on overall equipment effectiveness measurement. International Journal of Research in Industrial Engineering, 13(4), pp.376-383.

[51] Jurewicz, D., Dąbrowska, M., Burduk, A., Medyński, D., Machado, J., Motyka, P. and Kolbusz, K., 2023, September. Implementation of total productive maintenance (TPM) to improve overall equipment effectiveness (OEE) - Case study. In International Conference on Intelligent Systems in Production Engineering and Maintenance (pp. 543-561). Cham: Springer Nature Switzerland.

[52] Gelaw, M.T., Azene, D.K. and Berhan, E., 2024. Assessment of critical success factors, barriers and initiatives of total productive maintenance (TPM) in selected Ethiopian manufacturing industries. Journal of Quality in Maintenance Engineering, 30(1), pp.51-80.

[53] Khosroniya, M., Hosnavi, R. and Zahedi, M.R., 2024. Enhancing operational performance in industry 4.0: The mediating role of total quality management and total productive maintenance at Zarharan industrial complex. International journal of industrial engineering and operational research, 6(1), pp.96-122.

[54] Tortorella, G.L., Saurin, T.A., Fogliatto, F.S., Tlapa Mendoza, D., Moyano-Fuentes, J., Gaiardelli, P., Seyedghorban, Z., Vassolo, R., Cawley Vergara, A.F.M., Sunder M, V. and Sreedharan, V., 2024. Digitalization of maintenance: exploratory study on the adoption of Industry 4.0 technologies and total productive maintenance practices. Production Planning & Control, 35(4), pp.352-372.

[55] Samadhiya, A., Agrawal, R. and Garza-Reyes, J.A., 2024. Integrating industry 4.0 and total productive maintenance for global sustainability. The TQM Journal, 36(1), pp.24-50.

[56] Meza Jiménez, J., Cárdenas Velasco, H.E., Escamilla López, M. and Quintana Alvarado, J., 2024. Total productive maintenance (TPM). Lean Manufacturing in Latin America: Concepts, Methodologies and Applications, pp.263-284.

[57] Sangel, R.O., Pablo, A.D., Eboras, A.V. and Namoco Jr, C.S., 2024. Potential of implementing total productive maintenance (TPM) on a small-scale machine shop. Journal of Harbin Engineering University, 45(9), pp.150-156.

[58] Amrina, E. and Firda, S., 2024, February. Evaluation model of total productive maintenance implementation for cement plant. In AIP Conference Proceedings (Vol.

2710, No. 1). AIP Publishing.

[59] Wilson, E., Amgbari, C. and Jacob, U., 2024. Hybrid implementation of total productive maintenance (TPM): A case study of a brewery. International Journal of Applied and Advanced Engineering Research.

[60] Flagg, M.I. and Amadi, N.S., 2024. Utilization of total productive maintenance techniques for quality improvement of electrical workshop by technical colleges in Rivers State. International Journal of Modern Innovations and Knowledge, 5(2), pp.1-11.

[61] Okoro, G.O., 2024. Total productive maintenance (TPM) implementation and overall equipment effectiveness (OEE) in manufacturing firms in RIVERS STATE. BW Academic Journal, 1(3), pp.113-146.

[62] Herrera-Barreda, I., 2024. Enhancing operational efficiency in textile SMEs: Integrating lean manufacturing and total productive maintenance for superior performance. 5th Asia Pacific Conference on Industrial Engineering and Operations Management Tokyo, Japan, September 10-12, 2024.

[63] Ardi, M., Sutanto, A. and Susilawati, A., 2023. Analysis of effectiveness of cut size line machines based on total productive maintenance (TPM) and analytical hierarchy process (AHP)-A case study. Journal of Ocean, Mechanical and Aerospace-science and engineering-, 67(3), pp.109-117.

[64] Mohad, F.T., Gomes, L.D.C., Tortorella, G.D.L. and Lermen, F.H., 2024. Operational excellence in total productive maintenance: Statistical reliability as support for planned maintenance pillar. International Journal of Quality & Reliability Management.

[65] Rathi, S.S., Sahu, M.K. and Kumar, S., 2024. Implementation of total productive maintenance to improve productivity of rolling mill. Indian Journal of Engineering & Materials Sciences Vol. 30, December 2023, pp. 882-890.

[66] Gomaa, A.H., 2025. Maintenance 4.0: Optimizing Asset Integrity and Reliability in Modern Manufacturing. International Journal of Inventive Engineering and Sciences (IJIES), 12(2), pp.18-26, pp. 18-26.

[67] Gomaa, A.H., 2025. RCM 4.0: A Novel Digital Framework for Reliability-Centered Maintenance in Smart Industrial Systems. International Journal of Emerging Science and Engineering (IJESE), 13(5), pp. 32-43.

[68] Gomaa, A.H., 2025. Smart Maintenance in Industry 4.0: Optimizing Equipment Performance Through Digital Twins and Lean Six Sigma Integration. IUP Journal of Mechanical Engineering, 18(1), pp.7-31.