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Predictive Maintenance Adoption in Southeast Asia's Aviation MRO: A Systematic TOE-Based Analysis

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ABSTRACT

The aviation industry in Southeast Asia (SEA) is undergoing significant digital transformation, with Predictive Maintenance (PdM) emerging as a critical innovation within Maintenance, Repair, and Overhaul (MRO) operations. Despite global advancements in PdM technologies, such as Internet of Things (IoT) sensors, artificial intelligence (AI) analytics, and digital twins, adoption across SEA remains inconsistent. This study investigates PdM adoption across the region's MRO sector using the Technology-Organization-Environment (TOE) framework to assess national readiness levels, systemic barriers, and strategic enablers. Employing a qualitative methodology that integrates a Systematic Literature Review (SLR) and Document Analysis of scholarly and industry sources published between 2013 and 2024, the study reveals stark disparities in PdM maturity. Singapore and Malaysia exhibit high readiness due to advanced infrastructure, coordinated policy support, and public–private collaboration. In contrast, the Philippines, Vietnam, and Indonesia face persistent challenges related to fragmented governance, workforce capability gaps, and minimal integration of PdM tools into core operations. Organizational inertia, technical skill shortages, and regulatory inconsistencies are identified as critical inhibitors. The TOE framework proves effective in capturing the interplay of contextual factors influencing PdM implementation in highly regulated, safety-critical industries. The findings inform a strategic roadmap emphasizing workforce development, regulatory harmonization, and cross-sector alignment as prerequisites for successful PdM adoption. Future research should focus on in-depth case studies, empirical validation of TOE constructs, and actor-specific adoption dynamics to advance theoretical and practical understanding.

1. INTRODUCTION

The aviation industry is undergoing a profound transformation driven by the integration of digital technologies into Maintenance, Repair, and Overhaul (MRO) operations. At the forefront of this shift is Predictive Maintenance (PdM)—a proactive, data-driven approach that utilizes real-time monitoring, advanced analytics, and machine learning to anticipate equipment failures before they occur (Praxie, 2023). Unlike traditional reactive or time-based preventive maintenance, PdM enables interventions only when necessary, based on the actual condition of components. This paradigm shift enhances safety, reliability, and operational cost-efficiency.

Global aviation leaders have adopted Predictive Maintenance (PdM) by leveraging technologies such as Aircraft Health Monitoring Systems (AHMS), Internet of Things (IoT) devices, and Artificial Intelligence (AI). Notable examples include Rolls-Royce's TotalCare and Boeing's data-driven maintenance strategies, both of which utilize predictive analytics to reduce Aircraft on Ground (AOG) events and optimize asset utilization (Rolls-Royce, 2017; Boeing, 2024). Leading MRO providers such as Lufthansa Technik have deployed machine learning and digital twin platforms, signaling a transition toward intelligent, resilient maintenance systems (Lang, 2023; Pelt et al., 2019). As shown in Figure 1, digital integration allows technicians to use tablet-based tools for engine inspections, providing real-time data access and enhanced diagnostic precision (AMRC, 2018).

However, while predictive maintenance is gaining momentum globally, its adoption in Southeast Asia (SEA) remains fragmented and underexplored. Despite SEA's projected rise as a central aviation hub, the region faces persistent barriers, including uneven digital infrastructure, limited organizational readiness, insufficient technical expertise, and regulatory gaps (Budiman et al., 2024; Franciscus, 2021). Singapore has emerged as a regional

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leader in MRO capability; however, neighboring countries such as Vietnam, Indonesia, and the Philippines continue to struggle with implementing PdM systems at scale (Guiguzi, 2022; Ayeni et al., 2011).

What makes this issue particularly urgent is the lack of systematic, multi-country analyses that assess PdM readiness and adoption across the region. Existing literature tends to focus on global best practices or isolated national case studies, offering limited insight into the diverse technological, organizational, and environmental realities within Southeast Asia. This fragmented understanding hampers strategic investment, cross-border policy alignment, and the regional scaling of innovative maintenance practices.

To address this gap, the present study investigates the adoption of predictive maintenance (PdM) technologies in Southeast Asia's aviation Maintenance, Repair, and Overhaul (MRO) sector through the lens of the Technology-Organization-Environment (TOE) framework. The study focuses on assessing readiness levels, identifying implementation barriers, and uncovering strategic opportunities for PdM integration across the region. Employing a qualitative methodology that combines a Systematic Literature Review (SLR) with Document Analysis of regulatory reports and industry publications, this research provides a structured, region-specific evaluation of PdM adoption. The TOE framework categorizes the key influencing factors into three interrelated dimensions: technology, organization, and environment. The technology dimension considers the availability, compatibility, and sophistication of PdM tools, including sensors, analytics platforms, and integration systems. The organization dimension examines internal capacity, organizational culture, leadership support, and digital readiness within MRO facilities. The environmental dimension focuses on external contextual elements such as policy frameworks, regulatory mandates, infrastructure quality, and national investment in digital aviation capabilities.

By applying this multidimensional framework, the study provides a comprehensive understanding of PdM adoption dynamics across Southeast Asia. It lays the groundwork for evidence-based strategies that enhance digital maturity, facilitate policy alignment, and enable targeted capacity-building initiatives.

2. Literature Review

A. Introduction to Predictive Maintenance in Aviation

Predictive Maintenance (PdM) is a proactive, data-driven maintenance strategy that uses real-time monitoring, advanced analytics, and machine learning to detect early

Figure 1: Digital integration in aviation MRO: A technician uses a tablet-based system to perform predictive maintenance inspections on an aircraft engine nacelle, illustrating real-time data access and enhanced diagnostic capabilities (Source: AMRC, 2018)

signs of component degradation and prevent unexpected failures (Praxie, 2023). In aviation, PdM transforms traditional Maintenance, Repair, and Overhaul (MRO) practices through Aircraft Health Monitoring Systems (AHMS), onboard sensors, and intelligent analytics platforms. These tools enable proactive interventions, improving operational reliability and reducing unplanned downtime (Llopis, 2024).

B. Evolution of Maintenance Strategies

Aircraft maintenance has evolved from a reactive to a preventive and, more recently, to a predictive approach. Reactive maintenance addressed issues post-failure, often resulting in high costs and safety risks (Dundas, 2025). Preventive maintenance improved reliability through scheduled checks but could lead to over-maintenance. Predictive maintenance (PdM), the most advanced phase, integrates real-time data, historical logs, and flight metrics to inform condition-based maintenance. Airlines such as Lufthansa Technik and Boeing now utilize machine learning to schedule maintenance precisely when needed (Boeing, 2024), thereby optimizing efficiency, reducing AOG events, and maximizing resource utilization.

C. Technological Enablers of PdM

The implementation of Predictive Maintenance (PdM) in aviation is made possible through the integration of a suite of interconnected technologies that enable the collection, transmission, and real-time analysis of aircraft data. At the forefront are advanced sensor technologies that monitor critical parameters, including vibration, temperature, and pressure. These sensors are vital for detecting early anomalies in engines, avionics, and structural systems, allowing maintenance teams to take timely and precise action (Singh, 2023). Complementing this is the Internet of Things (IoT), which facilitates seamless connectivity between aircraft systems and ground-based platforms. The

Internet of Things (IoT) enables Real-time diagnostics, tool tracking, inventory management, and process automation within Maintenance, Repair, and Overhaul (MRO) environments improve operational visibility and reduce turnaround times (McFarlane, 2024). Additionally, Artificial Intelligence (AI) and Machine Learning (ML) technologies play a pivotal role by analyzing large volumes of historical and real-time data to identify patterns, forecast failures, and inform maintenance decisions. Programs like Rolls-Royce's TotalCare® exemplify the use of AI-powered analytics in monitoring engine health and automating maintenance scheduling (Rolls-Royce, 2017). Together, these technologies form the backbone of intelligent MRO ecosystems, enabling data-informed decision-making, minimizing unplanned downtime, and enhancing cost-efficiency across the aviation maintenance lifecycle.

D. Benefits of PdM in MRO Operations

Studies confirm that Predictive Maintenance (PdM) enhances safety through early fault detection, reduces unplanned maintenance events, and improves fleet availability (Monisha, 2023; Fedorov et al., 2021). PdM strategies also yield substantial cost savings; integration of Remaining Useful Life (RUL) estimation into planning can reduce costs by up to 53% compared to traditional methods (Mitici et al., 2023; Pater & Mitici, 2021). By shifting to data-informed maintenance, airlines minimize AOG incidents and optimize operational performance (Stanton et al., 2022).

E. Global vs. Southeast Asia Trends in PdM Adoption

Globally, leading MROs, such as Lufthansa Technik, have integrated machine learning, digital twins, and cloud platforms to enhance predictive accuracy and minimize unplanned downtime (Pelt et al., 2019; Lang, 2023). In contrast, many Southeast Asian countries are still in the process of building foundational digital capabilities. Singapore stands out as a regional leader due to its strong digital infrastructure and regulatory support. However, other countries in the region, such as the Philippines, Vietnam, and Indonesia, remain in the early stages of PdM adoption, hindered by fragmented policies, limited technical capacity, and underinvestment in digital infrastructure (Budiman et al., 2024; Franciscus, 2021). The lack of coordinated region-wide strategies and disparities in digital maturity have contributed to inconsistent and often isolated PdM implementation efforts across the region (Nam et al., 2023). These contrasting trends are summarized in **Table 1**, which compares global benchmarks with the current state of PdM readiness across Southeast Asian countries, highlighting key gaps and opportunities for alignment.

Table 1. Comparative Assessment of PdM Readiness Across Global and Southeast Asian Regions. This table summarizes the levels of infrastructure, tool adoption, regulatory support, and organizational readiness related to the implementation of Predictive Maintenance (PdM).

Region	Infrastructure	PdM Tool Adoption	Regulatory Support	Organizational Readiness
Global (EU, NA)	Advanced	High	Strong and standardized	High
Singapore	Advanced	High	Strong	High
Malaysia	Developing	Moderate	Moderate	Moderate
Philippines	Limited	Low	Developing	Low
Indonesia	Limited	Low	Weak	Low

F. Barriers to Digital Adoption in Aviation

Several interrelated barriers hinder the adoption of Predictive Maintenance (PdM) in aviation. Technologically, issues such as poor data integration, cybersecurity concerns, and incompatibility with legacy systems delay implementation (Yordanova, 2023; Ranjan et al., 2023). Organizationally, resistance to change, limited digital skills, and misalignment in leadership weaken internal readiness (Kutnjak & Pihir, 2019; Maratis et al., 2024). From an environmental perspective, unclear regulations, the absence of standardized digital protocols, and high initial investment costs contribute to uncertainty and reluctance among stakeholders (Ogundare et al., 2024; Thumati et al., 2020). Overall, successful digital transformation in Maintenance, Repair, and Overhaul (MRO) requires not only technological upgrades but also profound cultural and structural shifts across the aviation ecosystem (Scott, 2007; Rana et al., 2013).

G. Theoretical Framework: Technology-Organization-Environment (TOE)

To systematically assess the adoption of Predictive Maintenance (PdM) in Southeast Asia's aviation Maintenance, Repair, and Overhaul (MRO) sector, this study adopts the Technology-Organization-Environment (TOE) framework developed by Tornatzky and Fleischer (1990). The TOE framework was selected over alternative models, such as the Technology Acceptance Model (TAM), Diffusion of Innovations (DOI), and Unified Theory of Acceptance and Use of Technology (UTAUT), due to its comprehensive, multi-level structure unlike TAM and UTAUT, which primarily focus on individual user behavior, or DOI, which emphasizes the innovation lifecycle, TOE accounts for a broader set of organizational and contextual variables that are critical to enterprise-level technology adoption, especially in complex, regulated environments such as aviation MRO.

The technology domain in TOE considers the availability, compatibility, complexity, and maturity of predictive maintenance (PdM) tools, including sensor systems, aircraft health monitoring systems (AHMS), artificial intelligence (AI), machine learning (ML), and digital twins. Studies such as Rolls-Royce's TotalCare (Rolls-Royce, 2017) and Lufthansa Technik's use of machine learning (Lang, 2023; Pelt et al., 2019) demonstrate how mature predictive maintenance (PdM) technologies enhance forecasting accuracy and operational efficiency. The organizational domain emphasizes internal readiness factors, including workforce capability, leadership support, digital skills, financial resources, and openness to innovation. Research by Kutnjak and Pihir (2019) and Maratis et al. (2024) highlights how organizational resistance, skill gaps, and poor strategic alignment can hinder the implementation of PdM—even when technology is available.

The environment domain captures external influences, including regulatory frameworks, policy support, infrastructure, and competitive or customer-driven pressures. Prior studies, such as those by Ogundare et al. (2024) and Thumati et al. (2020), have demonstrated that ambiguity in aviation regulations, a lack of standardized protocols, and limited infrastructure can hinder the adoption of advanced maintenance systems in developing regions. By applying the TOE framework, this study offers a structured, multi-country analysis of PdM readiness in Southeast Asia. The framework enables the categorization of findings from systematic literature review and document analysis, allowing for the identification of regional trends, systemic barriers, and strategic enablers. This approach ensures a balanced understanding of the technological, organizational, and environmental dynamics shaping PdM adoption, providing actionable insights for MRO stakeholders, policymakers, and aviation regulators in the region.

3. Methodology

A. Research Design

This study utilized a qualitative research design that combined a Systematic Literature Review (SLR) with Document Analysis to investigate the adoption of predictive maintenance (PdM) in aviation Maintenance, Repair, and Overhaul (MRO) facilities within Southeast Asia. The SLR approach was selected to ensure a structured and comprehensive examination of relevant scholarly literature, grounded in established academic practices. It provided a foundation for exploring existing theories, frameworks, and empirical findings related to the implementation of PdM technologies, particularly in the aviation and digital transformation contexts.

In addition to the literature review, Document Analysis was employed as a complementary method to examine secondary sources, including policy documents, technical reports, white papers, and publications from recognized international and regional aviation bodies. This design enabled the study to draw from both academic and institutional perspectives, offering a broader understanding of PdM adoption within the region. The integration of these two qualitative methods established a rigorous foundation for investigating the technological, organizational, and environmental factors influencing PdM implementation, as guided by the Technology-Organization-Environment (TOE) framework.

B. Data Collection and Search Strategy

The data for this study were gathered using two qualitative methods: a Systematic Literature Review (SLR) and Document Analysis, both structured around the Technology-Organization-Environment (TOE) framework. The SLR targeted academic publications from 2013 to 2024, using four major databases—Scopus, Web of Science (WOS), ScienceDirect, and Google Scholar—chosen for their comprehensive coverage of peer-reviewed literature in aviation, engineering, and digital transformation. A targeted keyword strategy was applied, incorporating terms such as "Predictive Maintenance," "Aviation MRO," "Aircraft Health Monitoring," "PdM adoption," and "Southeast Asia." Boolean operators and database-specific filters were used to enhance search precision.

The selection of the 2013–2024 timeframe was based on both theoretical relevance and empirical significance. The year 2013 marks a turning point in scholarly attention toward Predictive Maintenance (PdM) in aviation, with the early adoption of digital technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) in Maintenance, Repair, and Overhaul (MRO) operations. This period also aligns with national digitalization strategies and policy reforms in Southeast Asia aimed at modernizing the aviation sector. The upper bound of 2024 ensures the inclusion of recent innovations and reflects the latest empirical developments and regulatory shifts affecting PdM deployment in the region. Collectively, this 12-year window provides a balanced lens for assessing both foundational trends and current readiness levels.

Articles were included if they were published in English, appeared in peer-reviewed or reputable open-access outlets, and explicitly addressed PdM in the aviation context. Studies were excluded if they were duplicates, lacked full-text access, or focused on non-aviation sectors. Following the PRISMA 2020 framework, the article selection process involved four stages: identification, screening, eligibility, and inclusion. This process yielded 56 qualifying studies for thematic synthesis. The detailed selection procedure is depicted in **Figure 2**, while an overview of the included studies covering year, method, and focus is summarized in **Table 2**.

To complement the SLR, a Document Analysis was conducted by reviewing industry reports, white papers, and strategic documents from recognized aviation authorities and organizations, including the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA), and national aviation regulators across ASEAN. Additionally, operational and strategy-related documents from major MRO providers such as Lufthansa Technik, ST Engineering, and SIA Engineering were analyzed. Documents were included if they were published between 2013 and 2024, addressed

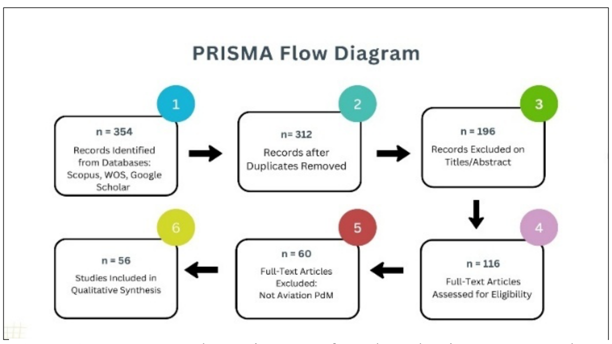

Figure 2: PRISMA Flow Diagram of Study Selection Process. The visual illustrates the step-by-step screening process for qualitative synthesis, highlighting exclusions at each stage.

predictive maintenance implementation or planning, and offered insights applicable to Southeast Asian contexts. Priority was given to materials that provided regional perspectives and practical frameworks for the adoption of predictive maintenance (PdM). This dual-method approach enabled the triangulation of data from both academic and industry sources, thereby enhancing the validity, reliability, and contextual richness of the study's findings.

C. Data Analysis

The analysis of data collected from the Systematic Literature Review (SLR) and Document Analysis was guided by the Technology-Organization-Environment (TOE) framework, which provided a structured lens for categorizing and interpreting findings related to the adoption of Predictive Maintenance (PdM) in aviation Maintenance, Repair, and Overhaul (MRO) facilities. All relevant data were systematically coded into three core domains: technology, organization, and environment.

The technology domain encompasses technical aspects of PdM, including sensor systems, aircraft health monitoring, artificial intelligence, machine learning, and digital twin technologies. The organization domain captured internal factors such as workforce capabilities, leadership support, digital culture, and operational readiness. The environment domain focused on external influences, including regulatory frameworks, market dynamics, customer expectations, and the maturity of regional infrastructure.

To enhance the depth of analysis, an inductive thematic coding approach was employed to identify recurring patterns within the SLR and Document Analysis corpus. Each document was reviewed line by line to generate open codes, which were then clustered into higher-order categories aligned with the TOE framework. A total of 31 initial codes were identified and grouped into nine major themes—three under each TOE dimension. For example, under the "Technology" domain, themes included *Tool Integration Challenges*, *Data Interoperability Issues*, and *IoT-Driven Innovations*. Manual coding was conducted using a structured codebook developed during the first cycle of analysis, with axial coding applied to relate categories across documents. Sample excerpts and supporting quotes were extracted to validate each theme and ensure analytical richness. This multi-layered coding process enabled a nuanced understanding of readiness gaps, enablers, and inhibitors in the context of PdM adoption in Southeast Asia's MRO sector (see **Table 3)** for an overview of the thematic coding structure.

Table 2. Summary of Reviewed Studies (n = 56). This table presents the author(s), year, research method, and thematic focus of the studies included in the systematic review.

No.	Author(s)	Year	Method	Focus Area
1)	Abd Wahab et al.	2024	Systematic Review	PdM and Digital Twin
2)	Alomar & Yatskiv	2023	Qualitative Case Study	Digitalization in Aircraft MRO
3)	Ayeni et al.	2011	Survey and Analysis	Lean in MRO
4)	Budiman et al.	2024	Quantitative Case Study	Cost and Energy in MRO
5)	Franciscus	2020	Policy Review	Facility Development
6)	Kutnjak & Pihir	2020	SLR	Digital Transformation Challenges
7)	Lang	2023	Case Study	PdM with AVIATAR

8)	Lang et al.	2023	Case Study	PdM in Airlines
9)	Llopis	2024	Industry Blog	PdM Benefits
10)	Maratis et al.	2024	Organizational Review	Organizational Barriers
11)	Mitici et al.	2023	Simulation Study	RUL Modelling
12)	Ogundare et al.	2024	Policy Analysis	Regulatory and Economic Constraints
13)	Pelt et al.	2019	Case-Based Analysis	MRO Digital Analytics
14)	Scott et al.	2022	SLR	PdM in Military Aviation
15)	Singh	2023	Technical Overview	Sensor Tech
16)	Stanton et al.	2022	Exploratory Review	PdM Implementation
17)	Yordanova	2023	Barrier Analysis	Eco-innovation Barriers
18)	McFarlane	2024	Industrial Overview	IoT for Aviation
19)	Kabashkin & Perekrestov	2024	Conceptual Framework	Transition to Health Management
20)	Fedorov et al.	2021	Quantitative Modelling	PdM Predictive Models
21)	Khan	2022	Quantitative Analysis	AI for MRO
22)	Ganguly	2023	Simulation	Digital Twin
23)	Scott et al. (2022)	2020	Case Study	AI for MRO
24)	Nadaf	2021	Exploratory Review	PdM Strategy
25)	Nangia et al.	2024	SLR	PdM Strategy
26)	Rafique et al.	2020	Case Study	PdM Strategy
27)	Hirshman et al.	2023	Quantitative Analysis	Infrastructure Readiness
28)	Kumar et al.	2022	Quantitative Analysis	AI for MRO
29)	Guiguzi	2020	Quantitative Analysis	Policy Integration
30)	Vietnam MIC	2021	Exploratory Review	Digital Twin
31)	Saraswat & Agrawal	2023	Case Study	Policy Integration
32)	Fedorov & Pavlyuk	2021	SLR	Policy Integration
33)	Dangut et al.	2023	SLR	Policy Integration
34)	NEDA	2022	Case Study	PdM Strategy
35)	MITI	2020	Case Study	AI for MRO
36)	Heim et al.	2022	Exploratory Review	PdM Strategy
37)	Boeing	2024	Case Study	AI for MRO
38)	Patel et al.	2023	Exploratory	Future Outlook on PdM
39)	Sivanuja & Sandanayake	2024	SLR	AI for MRO
40)	University of Sheffield	2024	Case Study	Infrastructure Readiness
41)	Kommanaboina	2020	Exploratory Review	AI for MRO
42)	Spexet et al.	2020	Case Study	AI for MRO
43)	CAAM	2020	Quantitative Analysis	Infrastructure Readiness
44)	SNDGO	2020	Quantitative Analysis	Infrastructure Readiness
45)	Dibsdale	2020	Simulation	AI for MRO
46)	Efthymiou et al.	2020	Quantitative Analysis	Policy Integration
47)	Pater & Mitici	2020	Simulation	AI for MRO
48)	Fedorov et al. (2022)	2023	Case Study	Digital Twin
49)	Li	2022	Case Study	Digital Twin
50)	Oeppen Hill et al.	2023	Quantitative Analysis	AI for MRO
51)	DICT	2023	Simulation	Infrastructure Readiness

52)	Madaki et al.	2022	Simulation	PdM Strategy
53)	Kominfo	2021	Exploratory Review	Digital Twin
54)	Dundas	2024	SLR	AI for MRO
55)	CAAS	2022	Case Study	Infrastructure Readiness
56)	Thian	2020	Quantitative Analysis	Policy Integration

Following this classification, thematic analysis was conducted to extract deeper insights and identify common challenges, drivers, and contextual differences across academic sources and industry documents. To support synthesis, a series of tables and matrices was used to organize evidence across TOE dimensions, enabling side-by-side comparisons of insights and highlighting areas of convergence or divergence. This structured yet flexible approach provided a comprehensive understanding of the multidimensional factors shaping PdM readiness and adoption across the region.

Table 3. Thematic Coding Summary Aligned with TOE Framework. This table presents key themes and sample sub-themes identified through inductive coding of SLR and Document Analysis data, organized by the Technology-Organization-Environment domains.

TOE Domain	Theme	Sub-theme / Code	Illustrative Insight / Excerpt
Technology	Tool Integration Challenges	Legacy system incompatibility	"Many MROs still rely on analog tools incompatible with PdM."
Technology	Data Infrastructure Gaps	Low IoT readiness	"Sensor coverage remains partial in regional hangars."
Organization	Leadership and Strategy	Lack of executive buy-in	"Digital priorities are not embedded in core strategies."
Organization	Workforce Capacity	Skills mismatch	"Technicians lack training in predictive diagnostics."
Environment	Regulatory Ambiguity	Fragmented standards	"Different rules across ASEAN nations delay PdM adoption."

4. Analysis and Discussion

A. Technology Domain

A.1 Tool Adoption

Predictive Maintenance (PdM) tool adoption across Southeast Asia reveals a tiered landscape shaped by each country's technological maturity and institutional integration. At the forefront is Singapore, where PdM has become embedded in routine operations through the widespread use of real-time monitoring systems, predictive analytics, and integrated Aircraft Health Monitoring Systems (AHMS). This high adoption rate, estimated at 90%, is reinforced by coordinated national strategies that link innovation with policy execution. As emphasized in the CAAS Air Transport Industry Transformation Map, "Smart MRO powered by robotics, data analytics and smart sensors will be a key enabler of future competitiveness" (CAAS, 2018). A notable example is SIA Engineering's collaboration with Airbus Skywise, which enabled real-time diagnostics for A320 aircraft, demonstrating how ecosystem alignment accelerates operational outcomes.

Malaysia, while not as advanced, demonstrates steady progress with an estimated 75% adoption rate. Government initiatives under the Industry4WRD policy have helped MROs incorporate PdM-enabling technologies into their workflows. According to the Ministry of International Trade and Industry (MITI, 2018), "predictive maintenance and condition-based monitoring are critical for efficiency and safety improvements." This centralized support has driven moderate success in bridging the gap between policy and practice.

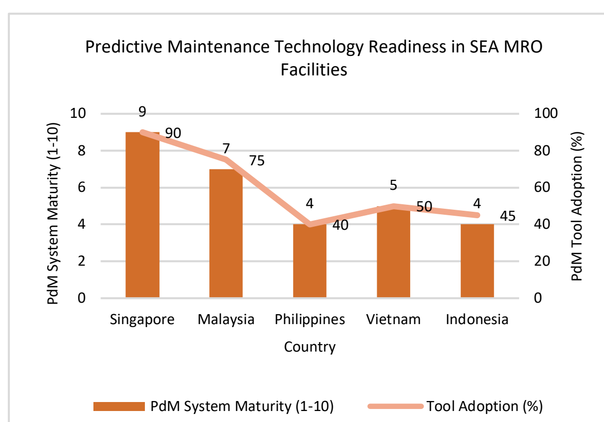

Figure 3: Predictive Maintenance Technology Readiness in SEA MRO Facilities. The chart presents the PdM system maturity (on a 1–10 scale) and the percentage of tool adoption in the MRO sectors of selected Southeast Asian countries.

Conversely, a second tier—comprising the Philippines, Vietnam, and Indonesia—exhibits partial and often fragmented implementation. Adoption rates in these countries range from 40% to 50%, with most PdM activities limited to vendor-led pilots or small-scale tests. For example, the Philippines' Civil Aviation Authority Advisory Circular 23-002 calls for MRO digitization but lacks enforceable frameworks to translate intent into practice (CAAP, 2023). Vietnam's National Digital Transformation Program similarly promotes innovative technology adoption, yet states that "aviation applications remain in the early pilot phase" (Vietnam MIC, 2020). A case reported by Lang et al. (2023) highlights this disconnect: a Vietnamese MRO installed PdM sensors but, without back-end analytics infrastructure, failed to generate meaningful outcomes.

These findings suggest that tool availability alone is insufficient. High-performing countries pair access to PdM technologies with integrated strategies and institutional accountability. In contrast, others continue to struggle due to uncoordinated deployment, underinvestment, and lack of operational alignment (see **Figure 3**).

A.2 System Maturity

System maturity in Predictive Maintenance (PdM) reflects not only technological deployment but also the depth of strategic alignment, regulatory coherence, and institutional readiness. The region demonstrates varying levels of maturity, shaped by national digital strategies and governance structures.

Singapore leads the region in terms of near-optimal system maturity, enabled by a synchronized framework of digital infrastructure, regulatory mandates, and robust industry collaboration. This alignment supports the deployment of full lifecycle predictive maintenance (PdM), enhancing operational continuity and data-driven decision-making across the MRO sector.

Malaysia represents a transitional case, showing structured but partial maturity. While key enablers such as regulatory plans and IT infrastructure exist, inconsistencies in cross-agency coordination and limited digital interoperability hinder seamless integration. The maturity trajectory here suggests progress, but not yet scale.

In contrast, the Philippines, Vietnam, and Indonesia reflect limited system maturity. These countries have initiated pilot projects and strategic plans, but fragmented platforms, outdated IT systems, and organizational silos hinder systemic transformation. For instance, in Vietnam, PdM-related activities are progressing under the national digital strategy; however, MROs lack integrated back-end infrastructure to support scalable solutions.

Overall, the maturity of PdM systems across Southeast Asia is shaped more by institutional cohesion, long-term planning, and digital governance capacity than by technological access. Advancing to higher levels of maturity will require countries to go beyond infrastructure investment and address deeper issues of interoperability, policy enforcement, and strategic continuity.

B. Training, Adoption Readiness, and Internal Barriers (Revised)

Organizational readiness—particularly in terms of workforce skills, leadership engagement, and institutional cohesion—is a key determinant of PdM implementation success across Southeast Asia. Countries differ widely in how internal capabilities support or hinder digital transformation efforts.

Singapore leads in organizational readiness, underpinned by sustained investments in training programs, strong executive buy-in, and a digital culture that encourages innovation. This combination enables effective integration of PdM tools into operational routines with minimal resistance.

Malaysia occupies a middle ground. While training initiatives and leadership interest are evident, they are inconsistently applied across MRO facilities. Challenges such as skill gaps and a lack of unified digital vision continue to limit transformation at scale.

The Philippines and Indonesia face more fundamental internal barriers, including limited access to PdM-specific training, siloed organizational structures, and low digital awareness among personnel. For example, a case reported by Budiman et al. (2024) illustrates that an Indonesian MRO's PdM pilot project failed to scale due to weak interdepartmental cooperation and ambiguous leadership roles, highlighting how internal fragmentation can undermine even well-funded digital initiatives.

Vietnam falls slightly ahead of this group, showing growing readiness in leadership support and training investment. However, it still contends with bureaucratic fragmentation that slows widespread adoption (**see Table 4**).

In summary, technical capacity alone is insufficient without organizational alignment. Developing PdM readiness requires not only upskilling initiatives but also strategic leadership, interdepartmental coordination, and a culture that supports digital change.

C. Environmental Readiness for PdM in SEA

Environmental readiness—comprising regulatory support, infrastructure capacity, and policy coordination—is a critical external enabler of PdM adoption across Southeast Asia. However, national progress varies substantially, shaped by institutional maturity and strategic focus. Singapore leads in this domain with a highly coordinated policy ecosystem. Regulatory foresight, cross-sectoral alignment, and sustained infrastructure investment have created favorable conditions for digital innovation in aviation.

According to the Smart Nation and Digital Government Office, "Singapore's regulatory frameworks are designed to support innovation and ensure interoperability in emerging technologies, including predictive analytics for transportation and logistics" (SNDGO, 2020). These factors have enabled the seamless deployment of Predictive Maintenance (PdM) across Maintenance, Repair, and Overhaul (MRO) operations.

Malaysia and Vietnam exhibit transitional environmental readiness. Both countries have introduced national policies to support aviation digitalization, but inconsistent enforcement and fragmented execution hinder full implementation. In Malaysia, the Civil Aviation Authority Strategic Plan 2021–2025 notes that "regulatory harmonization for digital technologies is still evolving" (CAAM, 2021). To address this, CAAM launched a regulatory sandbox in 2021, allowing selected Maintenance, Repair, and Overhaul (MRO) providers to test Predictive and Preventive Maintenance (PdM) solutions without full certification—an example of adaptive regulation that balances oversight with innovation. Vietnam's National Digital Transformation Program also promotes sector-specific digital strategies; however, gaps in execution limit the national-scale impact (Vietnam MIC, 2020).

The Philippines and Indonesia face more fundamental challenges. Both countries struggle with underinvestment, bureaucratic fragmentation, and limited policy clarity. The Philippine Digital Infrastructure Plan 2022–2026 acknowledges that "aviation systems remain one of the least digitized transportation domains due to fragmented ownership and underinvestment" (DICT, 2022). Indonesia's Digital Indonesia Vision 2045 echoes similar concerns, stating that "regulatory alignment across ministries and sectors is a persistent bottleneck" (Kominfo, 2021).

(PdM). In contrast, others require systemic reforms in infrastructure planning, inter-agency alignment, and institutional governance to translate strategic ambitions into operational outcomes.

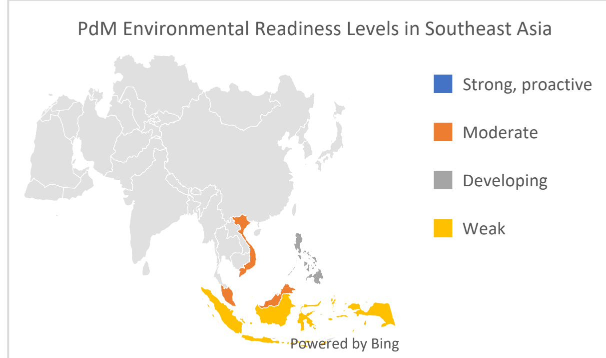

Figure 4: Environmental Readiness for Predictive Maintenance (PdM) Adoption in Southeast Asia. The map presents comparative data on regulatory influence, government policy support, and infrastructure readiness in five SEA countries

Comparing Southeast Asia (SEA) with global benchmarks highlights key performance gaps across all three TOE dimensions—technology, organization, and environment. While SEA countries are taking initial steps toward PdM adoption, the pace and depth of implementation fall short of global trends.

The most pronounced disparity lies in tool adoption, with global PdM implementation averaging around 78%, driven by mature ecosystems that integrate real-time monitoring, AI-driven diagnostics, and automated decision-making. In contrast, SEA countries average just 50%, with many deployments limited to pilot programs or partial integration. This suggests that while awareness is growing, structural limitations—such as legacy systems and vendor dependency—continue to impede region-wide scalability. See **(Figure 5)**.

Environmental readiness further differentiates Southeast Asia (SEA) from global benchmarks. In mature aviation markets, high readiness is driven by coherent national digital aviation strategies, cross-border regulatory harmonization, and sustained investments in smart

Table 4: Organizational Readiness for Predictive Maintenance (PdM) in Southeast Asia. The table outlines the availability of training programs, overall readiness for PdM adoption, and internal organizational barriers across MRO facilities in selected SEA countries.

Country	Training Programs Availability	Adoption Readiness	Internal Barriers
Singapore	Extensive	High	Low resistance; strong leadership support
Malaysia	Moderate	Moderate	Some resistance, moderate technical skills
Philippines	Limited	Low	High resistance; lack of awareness
Vietnam	Limited	Moderate	Moderate resistance; siloed departments
Indonesia	Minimal	Low	High resistance; limited strategic alignment

As shown in **Figure 4** above, environmental readiness across the region is stratified. Countries with centralized, innovation-friendly regulatory models are advancing the integration of Predictive and Preventive Maintenance

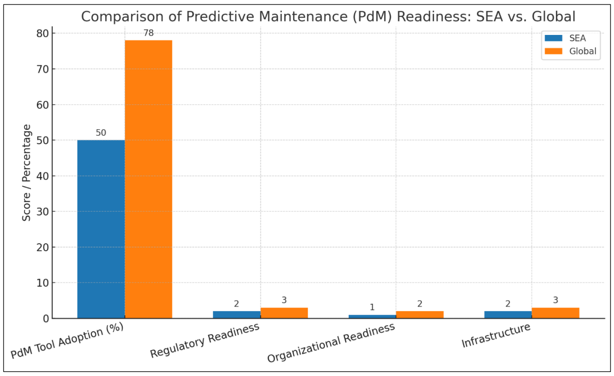

Figure 6: Comparison of Predictive Maintenance (PdM) Readiness: SEA vs. Global Trends. The chart illustrates comparative scores across four dimensions: tool adoption, regulatory readiness, organizational readiness, and infrastructure capacity.

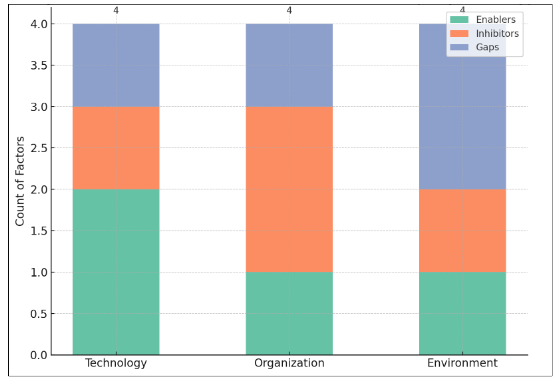

Figure 5. Distribution of Enablers, Inhibitors, and Gaps by Factor Type. This stacked column chart categorizes and quantifies the key factors influencing the adoption of Predictive Maintenance (PdM) in Southeast Asia.

infrastructure. In contrast, most SEA nations average a readiness score of 2 on a 3-point scale, with only Singapore approaching global standards. Across the region, regulatory ambiguity and inconsistent enforcement continue to limit the translation of policy intent into scalable, operational outcomes.

The disparity is even more pronounced in organizational readiness. Globally, many MROs have implemented structured change management programs, cross-functional digital training, and leadership-aligned innovation roadmaps. SEA, however, ranks lowest in this domain, with an average readiness level of 1.

As shown in **Figure 6**, the organization dimension is characterized by a high concentration of inhibitors and gaps, reflecting systemic internal challenges. These include skill mismatches, resistance to technological change, and siloed decision-making environments. Such barriers are particularly acute in lower-middle-income countries, where digital transformation initiatives often compete with more basic capacity-building needs.

In summary, SEA's PdM trajectory continues to lag behind global trends—not due to a lack of technological innovation, but because of fragmented systems and the absence of holistic integration across organizational and environmental dimensions.

Figure 6 underscores the critical need for coordinated system-wide reforms. Bridging these readiness gaps requires synchronized strategies that align institutional governance, workforce development, and digital infrastructure to enable sustainable PdM implementation across the region.

D. Cross-Country Synthesis of PdM Readiness in Southeast Asia

A cross-dimensional synthesis reveals persistent disparities in PdM readiness across Southeast Asia, shaped by deeper institutional and regulatory dynamics. Singapore demonstrates the most cohesive ecosystem, with centralized governance, aligned digital policies, and public-private coordination enabling full-scale PdM integration. As stated in the *Smart Nation Strategy*, "inter-agency digital cooperation and regulatory alignment ensure rapid deployment of innovation in regulated industries" (SNDGO, 2020), reinforcing its digital leadership in aviation MRO.

In contrast, Malaysia's progress is moderate but uneven, hindered by gaps between policy formulation and implementation, particularly in workforce training and cross-agency execution. The *Industry4WRD policy* acknowledges that "the translation of digital industrial

Table 5. TOE Heatmap of PdM Adoption Readiness in Southeast Asian MROs. This matrix color-codes the readiness levels across three TOE dimensions per country, revealing critical gaps and leading adopters.

Country	Technology Readiness	Organizational Readiness	Environmental Readiness
Singapore	High	High	High
Malaysia	Moderate	Moderate	Moderate
Vietnam	Low-Moderate	Moderate	Moderate
Philippines	Low	Low	Developing
Indonesia	Low	Low	Weak

strategies into sector-specific execution remains a work in progress" (MITI, 2018), highlighting the implementation gap in the aviation domain.

Vietnam demonstrates transitional readiness, with organizational and environmental support emerging, yet its technological infrastructure remains underdeveloped. According to the *National Digital Transformation Program*, "a lack of sector-specific digital standards and institutional coordination slows progress in high-potential areas, such as logistics and aviation" (Vietnam MIC, 2020). This reflects a broader pattern among emerging economies, where ambitious policies often outpace implementation capacity.

The Philippines and Indonesia exhibit the lowest readiness levels, constrained by fragmented institutions, weak regulatory enforcement, and limited funding. The *Philippine Digital Infrastructure Plan* admits that "digital aviation remains one of the least prioritized domains due to decentralization and inconsistent investment" (DICT, 2022). Similarly, Indonesia's *Digital Vision 2045* notes that "policy harmonization across ministries remains a key barrier to smart system integration" (Kominfo, 2021). These conditions stall PdM adoption and risk deepening the regional digital divide.

Importantly, adoption barriers persist even where enablers exist. This is due to misalignment across the TOE domains: technological tools or regulatory support alone cannot drive adoption without organizational readiness and strategic integration. Isolated enablers, in the absence of system-wide coordination, are insufficient to overcome structural resistance.

Table 5 above presents a TOE heatmap that summarizes these readiness levels, providing a strategic basis for targeted interventions across the region.

The disparities between countries are not solely technological; they reflect deeper institutional asymmetries. Singapore's integrated regulatory environment and centralized aviation governance allow for synchronized investments in infrastructure, digital training, and PdM implementation. In contrast, countries like the Philippines and Indonesia operate within fragmented aviation ecosystems, where regulatory agencies, MRO providers, and educational institutions lack coordination. Furthermore, budgetary limitations and policy discontinuity exacerbate these disparities. Malaysia's relative success illustrates how sustained investment and inter-agency alignment, though still evolving, can accelerate digital transformation. Bridging these gaps requires not only transferring technology but fostering institutional readiness through regional knowledge exchange, capacity building, and policy harmonization across Southeast Asia.

E. Framework Limitations

While the TOE framework effectively structures the multidimensional analysis of PdM readiness, it has inherent limitations. First, it offers a static snapshot of contextual factors and may not fully capture the dynamic, iterative nature of technological adoption in fast-evolving industries like aviation. Second, the model focuses primarily on organizational and environmental constructs at the meso level, overlooking micro-level behavioral factors (e.g., individual resistance, managerial cognition) and macro-level geopolitical influences (e.g., cross-border regulatory divergence). Finally, TOE assumes relatively equal weight across domains, whereas this study finds that organizational readiness may disproportionately shape adoption outcomes. Future research may benefit from integrating TOE with complementary models such as the Diffusion of Innovation (DOI) theory or Institutional Theory to capture deeper contextual and temporal nuances.

5. Conclusion And Future Work

Predictive Maintenance (PdM) adoption in Southeast Asia's aviation MRO sector remains highly uneven, shaped by disparities in institutional coordination, digital infrastructure, and organizational capacity. Singapore and Malaysia demonstrate advanced readiness, driven by targeted investments, policy coherence, and public-private collaboration. In contrast, the Philippines, Vietnam, and Indonesia face systemic limitations—fragmented governance, under-resourced infrastructure, and internal resistance—that restrict scalable PdM implementation.

Organizational readiness emerged as the most critical variable. MRO facilities with engaged leadership, structured training pathways, and cross-functional alignment consistently achieved more advanced PdM integration. Where these conditions were absent, adoption stalled, regardless of the availability of tools. Environmental readiness also played a defining role; countries with adaptive regulatory frameworks and investment in digital infrastructure moved faster and more effectively toward operational PdM maturity.

Technological access alone does not drive transformation. Sustainable PdM adoption requires institutional restructuring, regulatory modernization, and strategic capacity building. The TOE framework proved effective in diagnosing these interdependent factors, offering a structured methodology for assessing PdM adoption readiness across varying national contexts.

For PdM to scale across the region, stakeholders must prioritize integrated strategies that align technical capability with organizational agility and regulatory support. Without systemic alignment across these domains, regional efforts will remain fragmented and reactive. Advancing PdM in Southeast Asia demands coordinated action—embedding predictive technologies within broader digital aviation reforms to enhance operational efficiency, reduce maintenance risks, and position the region for long-term competitiveness.

A. Recommendation

Advancing PdM adoption in Southeast Asia's MRO sector requires tailored strategies that directly address capability gaps at the organizational, regulatory, and policy levels.

For MRO managers, the immediate priority is to institutionalize PdM-readiness by investing in workforce upskilling, integrating PdM into daily operational routines, and embedding a data-driven maintenance culture. Executive leadership must drive internal alignment by fostering cross-functional collaboration, setting measurable digital transformation goals, and forming strategic partnerships with technology providers to co-develop scalable, context-appropriate PdM solutions.

For policymakers, the focus should shift from broad digital aspirations to targeted aviation-specific interventions. Embedding PdM within national aviation strategies, linking funding incentives to measurable readiness benchmarks, and aligning technical education programs with industry needs are essential steps. Governments should also establish national centers of excellence and promote regional knowledge exchange to accelerate the transfer of capabilities across markets.

For aviation regulators, enabling the adoption of predictive and preventive maintenance (PdM) requires a shift toward adaptive, future-ready oversight. Updating maintenance certification protocols to include predictive analytics, introducing regulatory sandboxes to trial emerging technologies, and aligning standards across ASEAN will create a more enabling compliance environment. Regulators should also mandate secure data-sharing mechanisms and publish guidelines on PdM maturity to drive consistent implementation and benchmarking across Maintenance, Repair, and Overhaul (MRO) organizations.

Achieving widespread PdM adoption will depend on cross-sector coordination. Each stakeholder must move beyond pilot programs and symbolic strategies, taking concrete actions that collectively transform Southeast Asia's aviation maintenance ecosystem from a reactive to a predictive one, from fragmented to integrated, and from aspiration to execution.

To provide a clear and practical guide for MRO stakeholders, **Figure 7** below presents an infographic outlining the strategic roadmap for PdM integration across Southeast Asia. It highlights key milestones aligned with the Technology, Organization, and Environment dimensions over short, medium, and long-term horizons.

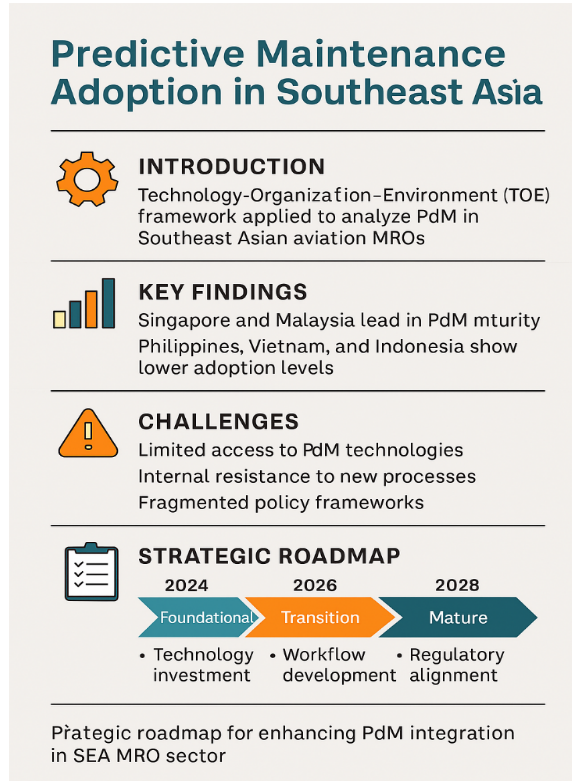

Figure 7: Predictive Maintenance Roadmap in SEA MRO Sector. This infographic illustrates key phases and recommended actions for PdM implementation, aligned with TOE-based maturity progression.

B. Future Research Directions

To further enrich the understanding of Predictive Maintenance (PdM) adoption in Southeast Asia's aviation sector, future research should focus on several key areas. First, in-depth case studies of MRO facilities across diverse contexts—ranging from technologically advanced hubs like Singapore to developing markets such as the Philippines and Indonesia—can offer valuable, grounded insights into the real-world implementation of PdM. These studies can uncover nuanced organizational behaviors, practical challenges, and success stories that go beyond generalized models.

Second, quantitative validation of the TOE framework through large-scale surveys and statistical modeling is essential. This would allow researchers to empirically test the strength of relationships between technological, organizational, and environmental factors and PdM adoption outcomes. Such data can provide evidence-based benchmarks for readiness and performance, making the TOE model more actionable for both academic and industry stakeholders.

Third, stakeholder-focused analysis is critical. Future studies should explore the perspectives of various actors involved in PdM adoption, including engineers, technicians, maintenance planners, top-level managers, and aviation regulators. By capturing the diverse priorities, motivations, and concerns of these groups, researchers can identify misalignments or synergies in expectations, which can inform more inclusive and strategic implementation approaches.

Ultimately, future research should aim to bridge the gap between theory and practice by developing frameworks, toolkits, and decision-support systems that guide MROs in their journey toward smart, predictive maintenance, while remaining sensitive to regional and operational realities.

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