Received 26 July 2025
Revised 29 January 2026
23 April 2026
Accepted 11 May 2026

Reducing human error in aircraft maintenance: a dual-framework analysis of smart technologies using SWOT and HFACS in Philippine MROs

Arthur Conlas Dela Peña
Department of Aircraft Maintenance Technology,
The National Aviation Academy of the Philippines, Pasay, Philippines

Abstract

Purpose – This study investigates the integration of structured human error analysis frameworks with smart technologies in Philippine maintenance, repair and overhaul (MRO) facilities. This study aims to identify recurring error patterns and assess organizational readiness for adopting advanced technologies to enhance aviation safety.

Design/methodology/approach – A qualitative, multiple-case study design was used. Data were collected through document analysis of maintenance error logs, safety manuals, and audit reports, supplemented by expert interviews with quality assurance personnel and supervisors. Human errors were classified using the Human Factors Analysis and Classification System (HFACS), while SWOT (strengths, weaknesses, opportunities, threats) analysis was applied to evaluate internal strengths and weaknesses, as well as external opportunities and threats related to the adoption of smart technology.

Findings – Results revealed that unsafe acts and organizational influences were the most prevalent error categories, primarily associated with procedural lapses, supervisory deficiencies, and technician fatigue. The SWOT analysis showed that while Philippine MROs are technologically aware, they are hindered by fragmented infrastructure, skills gaps, and regulatory uncertainties. Mapping HFACS-coded errors with emerging technologies demonstrated that augmented reality mitigates skill-based errors, artificial intelligence supports predictive fatigue management, radio frequency identification improves tool control, and Digital Twins enable proactive planning.

Originality/value – This study presents a novel integration of HFACS and SWOT as a dual-framework approach for linking human error analysis with strategic technology adoption. The proposed technology-safety road map offers practical advice for regulators, MRO operators, and training institutions to align safety culture with digital transformation. It also establishes a foundation for future research to validate the framework quantitatively and extend its application to military and unmanned aerial vehicle maintenance contexts.

Keywords Human factors, HFACS, Aircraft maintenance, MRO, Smart maintenance technologies, SWOT

Paper type Research paper

Smart and Resilient Transportation
Vol. 8 No. 2, 2026
pp. 168-188
Emerald Publishing Limited
e-ISSN: 2632-0495
p-ISSN: 2632-0487
DOI 10.1108/SRT-07-2025-0021

1. Introduction

Human error remains a critical concern in aviation safety, particularly in aircraft maintenance, where failures often originate from latent organizational conditions, incomplete inspections, documentation lapses, and supervisory breakdowns rather than real-time cockpit decision aids (ICAO, 2021; Hobbs and Williamson, 2003). Maintenance work is frequently performed under time pressure, fatigue, and incomplete information, conditions that intensify vulnerability to slips, lapses, and procedural deviations—especially in developing contexts such as the Philippines (Li and Harris, 2006; CAAP, 2022). Maintenance-related errors contribute to an estimated 12%–15% of aviation incidents, with potentially severe operational consequences (Reason, 2020; ICAO, 2023). In the Philippine setting, Civil Aviation Authority of the Philippines (CAAP)audit and oversight findings repeatedly flag improper installations, inadequate inspections, and weak documentation practices across MRO environments, indicating persistent gaps in systemic human-error management (CAAP, 2022).

A key practical challenge is that much of the available evidence for maintenance human factors is text-based (e.g. audit findings, occurrence narratives, corrective action reports, and SMS documentation). Such texts are heterogeneous in detail and terminology, shaped by reporting culture, and may omit critical operational context, complicating consistent interpretation and the extraction of actionable causal chains. While established frameworks support structured coding of such narratives, document-driven research must explicitly address ambiguity, missingness, and interpretive subjectivity to avoid overconfident causal claims.

Smart technologies—augmented reality (AR), artificial intelligence (AI), radio frequency identification (RFID) tool control, and digital twins—have demonstrated potential to reduce cognitive load, improve decision accuracy, and strengthen procedural compliance in maintenance settings (Ceruti *et al.*, 2018; Airbus, 2021; Hrúz *et al.*, 2021). However, implementation is not purely technical: adoption depends on workforce adaptability, infrastructure readiness, change management capacity, and regulatory enablement, which remain uneven across Philippine MROs (Ma *et al.*, 2022; Salas and Bernal, 2021). This scenario creates a dual problem: organizations must diagnose where and why human error emerges and determine which interventions are feasible and scalable under real constraints.

The Human Factors Analysis and Classification System (HFACS) is widely used to trace contributing factors across unsafe acts, preconditions, supervision, and organizational influences (Wiegmann and Shappell, 2003). However, in document-based corpora, HFACS can be diagnostic but not decisional: it classifies error mechanisms yet provides limited guidance for prioritizing interventions, assessing organizational readiness, or incorporating external constraints (e.g., regulatory clarity, vendor ecosystem, or investment capacity) that shape technology uptake. To address this limitation, this study adopts a dual-framework design that integrates HFACS + SWOT (strengths, weaknesses, opportunities, threats). HFACS structures the causal diagnosis of maintenance error signals from text evidence. SWOT also looks at both internal and external factors that affect whether smart technologies can be used, kept up, and turned into safety performance gains (Benzaghta et al., 2021). This integration provides a bridging logic from error diagnosis → feasibility assessment → strategy-aligned intervention mapping, which single-framework approaches often leave implicit.

Accordingly, this study integrates HFACS and SWOT to (1) classify common maintenance-related human errors in Philippine MRO contexts and (2) evaluate the readiness and strategic potential of smart technologies to mitigate these errors. Using document analysis, thematic coding, and framework synthesis, the study supports regulators, MRO leaders, and training institutions in designing human-centered modernization pathways aligned with CAAP's shift toward more predictive and performance-based oversight (ICAO, 2023; CAAP, 2022).

This study offers three contributions that extend prior HFACS-only or SWOT-only work. First, it introduces a decision-oriented dual-framework method (SWOT + HFACS) that links HFACS error-mechanism diagnosis to adoption feasibility and prioritization under organizational and regulatory constraints. Second, it operationalizes the technology–error linkage in an implementation-ready form through a technology–HFACS mapping explicitly tied to PSFs and structured documentary evidence, thereby strengthening interpretability in text-driven human factors research. Third, it provides a context-specific application to Philippine MRO environments, producing an actionable basis for capability building and technology selection in an emerging-market maintenance setting where evidence is predominantly documentary and adoption constraints are non-trivial.

2. Literature review

2.1 Human error in aircraft maintenance

Human error in aircraft maintenance continues to pose a critical threat to aviation safety, often resulting from complex interactions among organizational, environmental, and individual factors (ICAO, 2021). Aircraft maintenance technicians (AMTs) may commit slips, lapses, mistakes, or violations—as categorized by Reason (1990)—due to conditions such as time pressure, unclear procedures, fatigue, and poor supervision (Yazgan and Yılmaz, 2019; Nkosi *et al.*, 2020).

Globally, maintenance errors cause approximately 12%–15% of aviation incidents, and many of these incidents involve latent failures that are only discovered after flight operations (ICAO, 2023). In the Philippines, CAAP (2022) identified recurring issues in local MRO reports, including improper installation, incomplete inspections, and documentation lapses. These errors can lead to serious outcomes, including air turnbacks, runway excursions, or even in-flight decompression, as illustrated in the 1990 British Airways B747 case (Flight Safety Foundation, 2000). Empirical studies affirm the operational impact of these errors. Hobbs and Williamson (2003) noted that even minor oversights—like missing fasteners—can escalate into catastrophic failures. Li and Harris (2006) further emphasized that AMTs often face adverse working conditions that heighten error risk, particularly in regions such as the Philippines, where workforce shortages and tight schedules prevail.

While advancements in aviation technology have enhanced maintenance workflows, human error remains a leading safety challenge, often more consequential than errors made by flight crews (Reason, 2020). To address this, the industry is shifting toward predictive, data-driven approaches, integrating tools such as AI and proactive human factors assessments to minimize risks (Mendes *et al.*, 2022).

2.2 Smart technologies in aircraft maintenance

The integration of smart technologies into aircraft maintenance is transforming MRO operations by enhancing safety, improving efficiency, and reducing errors. Among the most impactful tools is AR, which overlays digital instructions onto components, reducing reliance on manuals and minimizing procedural errors. Trials conducted by Boeing and Lufthansa Technik have demonstrated AR's effectiveness in reducing cognitive load and improving task accuracy, particularly in complex installations (Ceruti *et al.*, 2018; Lufthansa Technik, 2020).

AI and predictive analytics are also reshaping maintenance by enabling early fault detection and data-driven decision-making. Platforms like Airbus Skywise and Honeywell Forge use real-time aircraft sensor data to predict failures and optimize maintenance schedules, thereby reducing unscheduled events and technician errors (Airbus, 2021; Kabashkin and Perekrestov, 2024).

In tool management, RFID systems, such as the Snap-on Level 5 Tool Control System, support foreign object damage prevention by enabling real-time tracking and accountability, ensuring tools are neither misplaced nor left onboard (Hrúz *et al.*, 2021). Other emerging technologies, including digital twins, internet of things-enabled sensors, and wearable or voice-guided maintenance systems, offer new layers of support. Digital twins allow diagnostics without physical disassembly, while wearables and voice systems enhance technician coordination and hands-free operation (Gao *et al.*, 2020; Mohammed *et al.*, 2024).

Additionally, virtual reality (VR) has proven to be an effective training tool in aircraft maintenance education. A recent study conducted in the Philippines demonstrated that VR significantly enhances student engagement and competency development, with notable improvements in knowledge retention, task accuracy, and problem-solving (Dela Peña, 2025). These innovations reflect the broader transition toward Aviation 4.0, where data integration, automation, and AI converge to streamline processes. However, challenges persist, particularly in regulatory alignment, system maturity, and implementation scalability (Ma, H.L. *et al.*, 2022). Continued collaboration among original equipment manufacturers (OEMs), regulators, and MROs is essential to harness the potential of smart technologies in maintenance fully.

2.3 Applications of SWOT analysis in aviation and technology adoption

Aviation professionals widely use the SWOT framework to evaluate strategic readiness and guide the adoption of emerging technologies. It provides a structured method for assessing internal capabilities and external challenges, particularly in maintenance, repair and overhaul (MRO) operations (Benzaghta *et al.*, 2021). In MRO settings, the SWOT framework has been used to align technology upgrades with workforce skills, regulatory demands, and infrastructure constraints (Chang *et al.*, 2019). Recent studies have applied the SWOT analysis to assess the implementation of smart technologies, including AI, AR and predictive maintenance. Salas and Bernal (2021) examined the adoption of predictive maintenance in Asian airlines, identifying internal resistance and regulatory gaps as key barriers while highlighting the operational benefits. Similarly, Šváb *et al.* (2024) conducted a SWOT analysis of AI integration in aviation, emphasizing the necessity of improved risk management strategies.

SWOT has also been instrumental in evaluating specific technologies, such as drone-based inspections, VR training and 3D printing. Taneja and Ghosh (2020) identified reduced inspection time as a key strength of drone usage, while concerns included data security and regulatory readiness. In VR-based AMT training, the SWOT analysis identified both accessibility challenges and opportunities for scalable, immersive learning. Šajbanová *et al.* (2021) used a similar SWOT analysis to evaluate 3D printing in aircraft manufacturing. Despite its broad applicability, traditional SWOT has limitations in prioritization and depth. Enhancements, such as integrating the Analytic Hierarchy Process (AHP) or evolutionary SWOT models, have been proposed to generate more actionable insights (Liangrokapart and Sittiwatethanasiri, 2022; Vlados, 2019). These hybrid approaches allow for better decision-making, particularly when navigating complex technology implementation scenarios in aviation.

2.4 Studies on human factors and error classification

Human factors are central to aircraft maintenance safety because procedures, tools, operating conditions, and organizational systems shape technician performance. Models such as SHELL and Reason's Swiss Cheese show how latent conditions combine with active failures to produce maintenance errors (ICAO, 2021; Wiegmann and Shappell, 2017). Common stressors include fatigue, time pressure, weak supervision, and poor communication, all of which increase slips, lapses, and violations (Rankin *et al.*, 2014; Padil *et al.*, 2018). HFACS is widely used to classify maintenance errors across unsafe acts, preconditions, supervision, and organizational influences (Hulme *et al.*, 2019; Li *et al.*, 2020). Studies show that maintenance events often arise not only from technician mistakes but also from supervisory and organizational conditions that contribute to missed inspections, documentation lapses, and procedural deviations (Harper and Bliss, 2023). However, HFACS alone is mainly diagnostic and offers limited support for intervention prioritization or implementation feasibility.

Related work on performance-shaping factors (PSFs), such as fatigue, workload, and training, helps explain how these conditions affect human error probability (HEP) in maintenance tasks (Franciosi *et al.*, 2019). Recent mitigation efforts emphasize FRMS, proactive screening, and just-culture reporting systems to support learning rather than blame (Miller *et al.*, 2023; Mrusek and Douglas, 2020). Overall, the literature supports a systems view of maintenance error and underscores the need to pair HFACS-based diagnosis with a feasibility-oriented approach to guide actionable interventions.

2.5 Literature synthesis and gap

HFACS is valuable for classifying maintenance-error mechanisms across system levels and shifting attention from individual blame to systemic causes. However, in document-based maintenance research, the evidence is often text-based, uneven in detail and context-sensitive, which can limit coding consistency and causal interpretation. More importantly, HFACS is primarily diagnostic: it identifies where failures occur but does not assess implementation feasibility, such as workforce readiness, digital maturity, regulatory clarity, vendor support, and resource constraints.

SWOT, on the other hand, looks at how well an organization can adopt new technologies and how outside factors affect that process. It doesn't say where mistakes happen or which systems need to be fixed. The gap, therefore, is that HFACS-only studies diagnose error pathways without prioritization under constraints, while SWOT-only studies assess readiness without linking strategy to specific human-error mechanisms. To address this gap, the present study integrates SWOT and HFACS to connect error diagnosis with feasibility assessment and support implementation-oriented prioritization of smart technologies in resource- and regulation-constrained MRO contexts.

3. Theoretical framework

3.1 Human Factors Analysis and Classification System

The HFACS is a validated framework for systematically identifying the underlying human factors that contribute to errors and accidents. Originally adapted from Reason’s Swiss Cheese Model, HFACS organizes causal factors into four hierarchical tiers: Unsafe Acts, Preconditions for Unsafe Acts, Unsafe Supervision, and Organizational Influences (Small, 2020; Wiegmann and Shappell, 2003). This taxonomy has been applied across diverse sectors, including aviation, maritime, health care, and unmanned aerial vehicle (UAV) operations (Hulme *et al.*, 2019; Widyanti and Reyhannisa, 2020).

In aviation maintenance, HFACS supports root cause analysis by identifying systemic contributors to human error, such as fatigue, poor supervision, or flawed organizational processes. Extensions of HFACS have incorporated tools like Bayesian networks and decision-making models to enhance analytical depth (Lyu *et al.*, 2019; Al-Rabeei *et al.*, 2022). While its reliability is generally high, researchers acknowledge that rater interpretation and contextual adaptation may influence its application (Oncu and Yildiz, 2014).

3.2 SWOT analysis framework

SWOT analysis is a classic strategic tool for assessing an organization's strengths, weaknesses, opportunities, and threats. It is widely used in the aviation, health care, education, and technology sectors to support evidence-based planning and the adoption of innovation (Benzaghta *et al.*, 2021; Siddiqui, 2021). In aviation, the SWOT analysis has been used to evaluate MRO strategies, assess the implementation of smart technology and inform AI integration in safety-critical environments (Šváb *et al.*, 2024; Javaherikhah and Sarvari, 2025).

While traditional SWOT is qualitative, researchers have proposed enhanced variants, such as SWOT-AHP or evolutionary SWOT, to improve prioritization and decision support (Liangrokapart and Sittiwatethanasiri, 2022; Vlados, 2019). Its strength lies in its adaptability and capacity to integrate contextual insights for strategic alignment.

4. Conceptual framework

This study applies a dual-framework approach that integrates HFACS and SWOT to examine human error and smart-technology adoption in Philippine MROs. As shown in Figure 1, the framework links maintenance error evidence with technology capabilities to generate strategic recommendations. Maintenance error reports, including incident logs, safety audits, and SMS manuals, are analyzed through HFACS to classify active failures and latent conditions across unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences (Wiegmann and Shappell, 2003).

At the same time, smart technologies such as AR, AI, RFID, and digital twins are assessed through SWOT to evaluate internal capabilities and external adoption conditions (Benzaghta *et al.*, 2021). The findings from both frameworks are then synthesized in a mapping stage that aligns specific error types with appropriate technology interventions, identifies strategic gaps, and supports recommendations for reducing human error, improving procedural compliance, strengthening technician performance, and promoting a more data-driven maintenance culture.

5. Methodology

5.1 Research design

This study used a document-based multiple-case design to examine how smart technologies may mitigate human error in selected MRO settings in Clark, Philippines. It integrates HFACS to classify error pathways across unsafe acts, preconditions, unsafe supervision, and

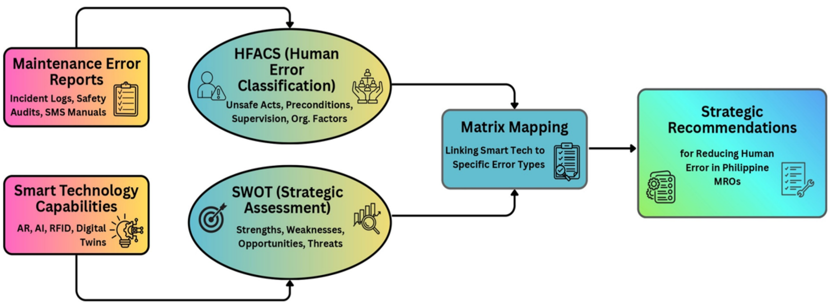

Figure 1. Conceptual Framework Integrating HFACS and SWOT for Strategic Reduction of Human Error in Philippine MROs

organizational influences, and it uses SWOT to assess internal capabilities and external constraints that affect technology adoption. Data were drawn from a bounded corpus of operational and governance records, including incident narratives, audit findings, SMS manuals, training and supervision records, and technology deployment logs. Qualitative analysis relied on thematic coding and HFACS tagging to identify recurring error mechanisms and latent organizational drivers.

To complement the qualitative analysis, the study applied lightweight quantitative triangulation through: (1) descriptive frequency profiling of HFACS-coded factors across cases; and (2) semi-quantitative estimation of how documented PSFs, such as workload, fatigue, procedural complexity, and supervision adequacy, may shift HEP when a technology is plausibly present. This approach is grounded in PSF–HEP logic in maintenance human reliability research (Franciosi *et al.*, 2019) and is consistent with HFACS-based extensions that support probabilistic reasoning when direct experiments are not feasible (Meng and Lu, 2022). Findings were synthesized in a technology–error mapping matrix linking each technology to its targeted HFACS factor(s), estimated direction or magnitude of HEP reduction, and relevant implementation constraints typical of aviation digitalization (Verhagen *et al.*, 2023).

5.2 Data sources

This study used two complementary evidence streams: (i) organizational documents and (ii) targeted expert inputs. Documentary sources included maintenance error and occurrence logs, SMS manuals, safety audit findings, corrective-action records, technology deployment logs, and relevant CAAP regulations and circulars. Together, these formed the primary corpus for HFACS-based identification of active and latent error mechanisms, consistent with HFACS-ME applications in maintenance records (Illankoon *et al.*, 2019).

To strengthen interpretation and reduce misreading of incomplete or institutionally shaped texts, expert clarification was obtained from quality assurance (QA) officers, safety managers, and senior line supervisors. Their inputs helped validate local reporting terminology, resolve ambiguous narratives, and distinguish routine conditions from exceptional events, consistent with recommended document-analysis practice and qualitative rigor safeguards (Dalglish *et al.*, 2020; Johnson *et al.*, 2020). After source identification and screening, data were collected through the structured three-phase procedure described below.

5.3 Data collection procedure

Data collection proceeded in three phases. First, relevant documents were obtained from participating MRO facilities in Clark and nearby aviation hubs, including internal maintenance error reports, SMS manuals, audit records, and applicable CAAP circulars. Document authenticity was verified with QA personnel, confidentiality procedures were observed, and records were screened using inclusion criteria aligned with the study's focus on human error and technology adoption.

Second, selected texts were deductively coded using HFACS. Each maintenance event was classified across unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences. To strengthen coding reliability, two coders used a shared HFACS codebook, piloted a subset of cases, and refined decision rules before full coding. Disagreements were resolved through coder reconciliation and, when necessary, adjudication by a third reviewer (QA/SMS focal person) using documentary evidence as the primary basis.

Third, technology-readiness content was analyzed through SWOT. Evidence statements were grouped into strengths, weaknesses, opportunities, and threats, with attention to enablers and barriers shaping feasible smart-technology integration. Optional feedback sessions with QA heads and SMS officers were used to clarify ambiguous narratives, validate borderline HFACS placements, and confirm the plausibility of SWOT interpretations in the operational context. A concise summary of this expert clarification process is provided in Appendix.

5.4 Data analysis

The study used a dual-framework analytic workflow combining deductive thematic analysis with structured cross-tabulation. Thematic analysis was selected because it supports theoretically driven coding while remaining flexible for heterogeneous text-based records (Braun and Clarke, 2022). Validated documentary sources, including incident narratives, audit findings and SMS manuals, were coded into HFACS tiers, while text on smart-technology capabilities and constraints was coded into SWOT categories, consistent with SWOT's role in organizing readiness and external pressures for strategic decision-making (Benzaghta *et al.*, 2021).

To connect both lenses, a technology-error matrix was constructed linking each technology, such as AR, AI analytics, RFID tool control and digital twins, to the HFACS-coded mechanisms it may interrupt. This step follows HFACS-based maintenance research showing the value of structured taxonomies for aggregating and mapping causal factors from deviation records (Illankoon *et al.*, 2019). A final synthesis matrix then traced the pathway from error mechanism to technology option to SWOT condition, showing how each intervention aligns with feasibility and strategic implications in the Philippine MRO context.

5.5 Quantitative estimation of error-probability reduction

To complement the qualitative HFACS–SWOT synthesis, the study included a lightweight quantitative module that generated bounded estimates of how smart technologies may reduce maintenance human error. HEP was operationalized through PSFs commonly documented in maintenance records, including workload or time pressure, fatigue, procedural complexity, communication quality, and supervision adequacy (Franciosi *et al.*, 2019). For each HFACS-coded error type in the corpus, dominant PSFs were identified and scored on a five-point ordinal scale, from very favorable or low risk to very unfavorable or high risk. A baseline HEP index and a technology-adjusted index were then derived through scenario-based rescoring under an assumed "with-technology" condition.

Technology effects were estimated through scenario-based pre/post scoring. For each mapped technology, such as AR, AI decision support, RFID tool control, and digital twins, an "as-is" and a "with-technology" scenario were specified using documented use cases and feasible integration assumptions. Expected PSF changes were converted into relative ΔHEP values. This approach is consistent with HFACS-based probabilistic reasoning where controlled experiments are impractical (Meng and Lu, 2022). To preserve implementation realism, ΔHEP estimates were interpreted alongside SWOT constraints and then incorporated into the Technology–Error Mapping Matrix as numeric or bounded estimates rather than purely qualitative labels (Mendes *et al.*, 2022).

5.6 Ethical considerations

This study followed established ethical standards for qualitative research involving organizational records. All documents obtained from participating MRO facilities were handled confidentially, and identifiable names, company codes, and sensitive operational details were anonymized during extraction and analysis. Access to internal records, including SMS manuals, error logs and audit reports, was obtained through formal requests and informed consent from authorized organizational representatives, typically quality assurance managers or safety heads.

Where expert validation sessions were conducted, participation was voluntary and supported by clear disclosure of the study's purpose, scope, and intended outputs. The research protocol was reviewed in accordance with institutional ethical guidelines and aligned with the data-handling policies of participating organizations. No data were used beyond the agreed research purpose, and no interviews were conducted without prior approval. These procedures were intended to preserve confidentiality, transparency, and respect for both institutional stakeholders and documentary sources.

6. Results

6.1 Identified human errors (HFACS-coded)

The analysis of maintenance documentation revealed that human errors in Philippine MRO environments predominantly fall under the "Unsafe Acts" category of the HFACS, accounting for 41 documented instances. These include skill-based slips, such as improper torque application and rule-based mistakes, like deviations from standard inspection protocols. The second most common category was "Preconditions for Unsafe Acts" ($n = 28$), which primarily involved fatigue, miscommunication, and environmental distractions such as noise or poor lighting.

"Unsafe Supervision" accounted for 15 occurrences, often associated with insufficient oversight, ambiguous task delegation, or failure to identify high-risk behaviors. Finally, "Organizational Influences" ($n = 10$) were observed in cases involving resource constraints, policy lapses, or conflicting priorities between safety and efficiency.

This distribution emphasizes that while individual actions are the most frequent, latent systemic and supervisory factors also significantly contribute to error incidence. The results validate the applicability of HFACS as a tool for tracing human error back to deeper organizational roots. Table 1 summarizes the identified errors by HFACS level, while Figure 2 visualizes the relative frequency of each error category.

6.2 Mapping smart technologies to HFACS-Coded errors and scenario-based ΔHEP estimates

Cross-case triangulation of maintenance error reports, SMS manuals, technology logs, and expert feedback was used to map smart technologies deployed or considered in Philippine MROs to HFACS-coded error mechanisms. HFACS localized where each technology may plausibly intervene across the four tiers (Unsafe Acts, Preconditions for Unsafe Acts, Unsafe Supervision, and Organizational Influences), while the quantitative module generated scenario-based bounded *Δ*HEP estimates for each technology–error pairing.

Table 1. Summary of maintenance errors classified by HFACS category

HFACS level	Frequency of errors	Common examples
Unsafe acts	41	Incorrect torque application; procedural lapses
Preconditions for unsafe acts	28	Fatigue, stress, communication breakdowns
Unsafe supervision	15	Inadequate task delegation; lack of verification
Organizational influences	10	Outdated tools; lack of standardized training

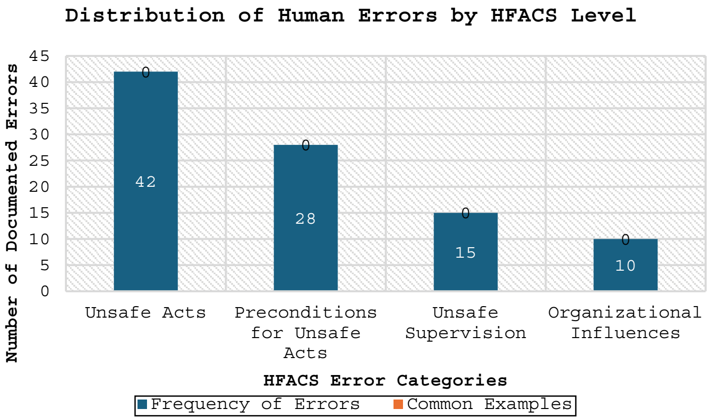

Figure 2. Frequency Distribution of Maintenance Errors by HFACS Category

Across the mapped technologies, AR aligned most consistently with unsafe acts, particularly where real-time overlays and step prompts may help reduce omission risk, procedural deviation, and documentation slips. AI and predictive analytics are aligned primarily with preconditions for unsafe acts and, to a lesser extent, with unsafe acts, especially in cases involving fatigue, attention, and workload-related PSFs. RFID tool tracking aligned most closely with unsafe supervision and organizational influences by strengthening traceability, accountability, and documentation integrity. Digital twins, although less prevalent in current practice, align mainly with organizational influences, where they may support planning, coordination, resource allocation, and scenario-based decision support for latent systemic conditions. Wearables and sensors were similarly associated with preconditions for unsafe acts through their potential to detect fatigue, stress, or reduced alertness.

Table 2 presents these technology–error relationships in a more explicit form by showing the targeted HFACS tier, key error types addressed, dominant PSFs affected, and the corresponding bounded *Δ*HEP estimates derived from the procedure described in subsection 5.5. These values should be interpreted as analytic, scenario-based estimates intended to support comparative reasoning rather than as directly observed empirical effects. Figure 3 complements this mapping by visualizing the relative pattern of estimated *Δ*HEP ranges across technologies and HFACS tiers.

6.3 SWOT matrix results

This study synthesized internal and external dimensions influencing the adoption of smart technologies in Philippine MROs through a SWOT-based lens. Internally, strengths include the operational presence of well-established safety management systems (SMS), which serve as procedural backbones for integrating new technologies. Several MROs have demonstrated adaptive capacity through successful pilot deployments of AR for line maintenance tasks and RFID for tool tracking, indicating a baseline digital readiness and positive workforce receptivity.

In contrast, weaknesses were evident in the fragmented IT infrastructure and siloed data systems, which hindered the seamless integration of technologies such as Digital Twins and predictive analytics. For instance, while some facilities maintain electronic error logs, others rely on manual processes, reflecting inconsistent digital workflows. Additionally, limited investment in technician upskilling for smart tools, such as AR-based troubleshooting or

Table 2. Scenario-based bounded estimates of ΔHEP for smart technologies mapped to HFACS error tiers

Smart technology	HFACS tier targeted	Key error types addressed	Dominant PSFs affected	ΔHEP (% relative reduction)*	Evidence basis
AR	Unsafe acts	Step omission, procedural deviation, documentation slips	Procedural complexity, memory dependence, checklist discipline, time pressure	20%–35%	Documentary corpus + expert feedback + PSF pre/post scoring (subsection 5.5)
AI	Preconditions for unsafe acts (primary); unsafe acts (secondary)	Fatigue-mediated lapses, attention degradation, workload-driven slips	Fatigue exposure, workload variability, vigilance/ attention	20%–35% (Preconditions); 5%–10% (Unsafe Acts)	Documentary corpus + expert feedback + PSF pre/post scoring (subsection 5.5)
RFID tool tracking	Unsafe supervision (primary); organizational influences (secondary)	Tool misplacement/FOD exposure, traceability gaps, accountability lapses	Supervision adequacy, control routines, documentation integrity	20%–35% (Unsafe Supervision); 10%–20% (Organizational)	Documentary corpus + expert feedback + PSF pre/post scoring (subsection 5.5)
Digital twins	Organizational influences	Planning/resource allocation errors, latent systemic conditions, deferred-risk accumulation	Planning quality, coordination, data/visibility, resource allocation	20%–35%	Documentary corpus + expert feedback + PSF pre/post scoring (subsection 5.5)
Wearables/ sensors	Preconditions for unsafe acts	Fatigue/stress exposure signals, degraded alertness	Fatigue/stress detection, workload tolerance, physiological strain	10%–20%	Documentary corpus + expert feedback + PSF pre/post scoring (subsection 5.5)

Note(s): ΔHEP values are analytic, PSF-based bounded estimates derived from documentary evidence, expert clarification and scenario-based pre/post scoring described in subsection 5.5. They are not directly measured empirical effects from experiments, surveys or operational intervention trials

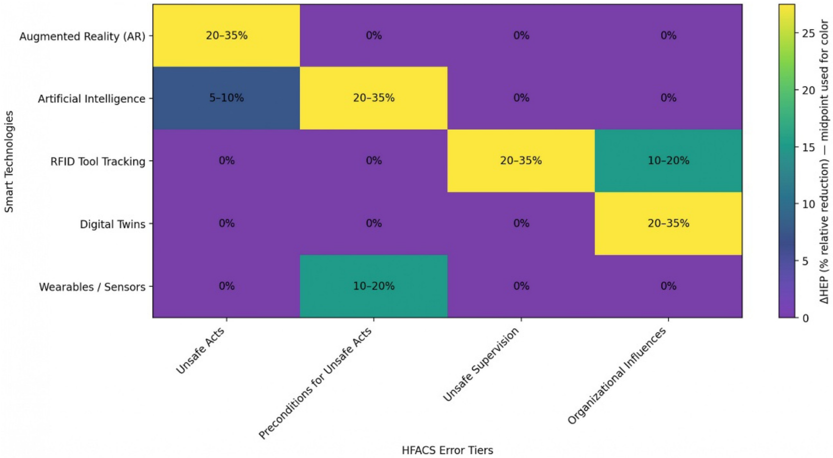

Figure 3. Estimated *Δ*HEP (%) by smart technology and HFACS tier (bounded ranges)

AI-based diagnostic platforms, creates gaps in the diffusion of innovation and operational scaling.

Externally, opportunities stem from the increasing global demand for aircraft maintenance services, particularly in Southeast Asia. This is coupled with the Civil Aviation Authority of the Philippines' (CAAP) regulatory shift toward digital oversight and the emergence of private sector interest in MRO digital transformation (e.g., OEM-led collaborations on AI diagnostics). These trends present opportunities to fund technology, align policy, and develop capabilities.

However,threatss persist. Regulatory ambiguity – especially regarding the use of AI and data in aviation maintenance – poses legal and compliance uncertainties. Resistance from segments of the maintenance workforce, particularly senior technicians accustomed to manual processes, may delay adoption. Additionally, the lack of harmonized digital standards across MRO operators leads to interoperability issues, complicating industry-wide innovation efforts.

As presented in Figure 4, these SWOT elements collectively map the current strategic landscape. Figure 5 visualizes this positioning, placing Philippine MROs in a “Tech-Aware but Infrastructure-Limited” quadrant. This suggests that while the strategic intent and operational interest in smart maintenance are evident, full-scale implementation remains constrained by infrastructural inconsistencies, training gaps and policy uncertainties. Addressing these barriers is critical to transitioning toward a more digitally mature and resilient MRO ecosystem.

6.4 Quantitative module results (ΔHEP)

Applying the quantitative module described in subsection 5.5, the mapped technologies produced scenario-based bounded *Δ*HEP estimates that vary by HFACS tier and are intended for comparative prioritization rather than empirical validation.

As summarized in Table 3, the larger bounded estimates appear where a technology plausibly addresses dominant PSFs linked to a given HFACS tier. AR was associated with unsafe acts, with estimated *Δ*HEP ranges of 20%–35%, reflecting its potential role in step

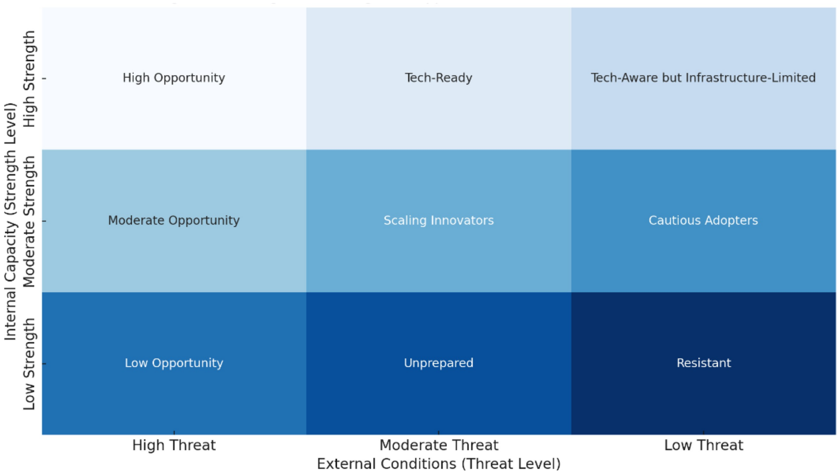

Figure 4. Strategic Positioning of MRO Tech-Readiness

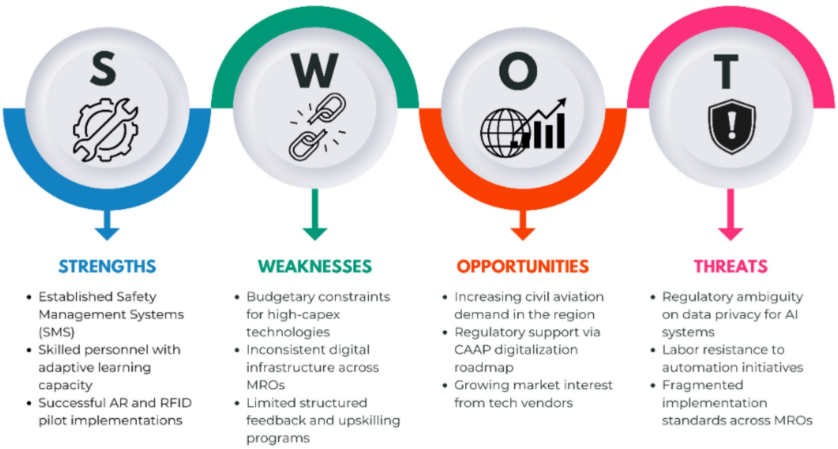

Figure 5. SWOT Matrix of Smart Technology Integration in Philippine MROs: Internal and External Factors Influencing Adoption Readiness

Table 3. Quantitative module outputs (*Δ*HEP) by technology and HFACS tier

Technology	HFACS tier	*Δ*HEP band (% relative reduction)	Midpoint used for visualization (%)
AR	Unsafe acts	20–35	27.50
AI	Preconditions for unsafe acts	20–35	27.50
AI	Unsafe acts	5–10	7.50
RFID tool tracking	Unsafe supervision	20–35	27.50
RFID tool tracking	Organizational influences	10–20	15.00
Digital twins	Organizational influences	20–35	27.50
Wearables / sensors	Preconditions for unsafe acts	10–20	15.00

guidance, omission control, and procedural support. AI showed its strongest estimated alignment with Preconditions for Unsafe Acts (20%–35%), where fatigue exposure, workload variability, and vigilance-related factors are more prominent, while its secondary alignment with Unsafe Acts was smaller (5%–10%). RFID tool tracking was associated with unsafe supervision (20%–35%) and, to a lesser extent, organizational influences (10%–20%), reflecting its potential contribution to stronger traceability, accountability, and control routines. Digital twins were mapped primarily to organizational influences, with bounded estimates of 20%–35%, where planning quality, coordination, and resource visibility are relevant. Wearables and sensors showed more moderate estimated effects for Preconditions for Unsafe Acts (10%–20%), particularly in relation to fatigue, stress and physiological strain monitoring.

Taken together, these outputs suggest that AR and selected AI applications may offer nearer-term value for task-level and precondition-related risk management, whereas RFID and digital twins may be more relevant for strengthening supervisory and organizational control structures. However, these ΔHEP values should be read as modeled comparative indicators within the study's analytic framework, not as validated effect sizes from experimental or operational intervention studies.

7. Discussion

This study interprets human error and smart-technology adoption in Philippine MROs through an integrated HFACS–SWOT lens. HFACS localizes where maintenance errors cluster across system tiers, while SWOT clarifies whether technology controls are realistically implementable under current operational and regulatory conditions. The findings show that unsafe acts—particularly skill-based slips and procedural deviations—were most frequently documented, followed by preconditions for unsafe acts such as fatigue, miscommunication, and inadequate task planning. Supervisory and organizational contributors were also evident in audits and safety records, indicating that maintenance error is sustained by latent system conditions rather than by frontline actions alone.

When these patterns are mapped to technology options, AR and RFID align most strongly with execution control and traceability, whereas AI and digital twins align more with planning, forecasting, and system-level support. SWOT findings, however, show why these alignments do not automatically produce realized benefits. AR, for example, may help reduce procedural deviations, but its effectiveness depends on workflow standardization and IT integration. Likewise, AI-enabled fatigue or forecasting tools depend on reliable data architecture and consistent reporting quality. In this sense, Philippine MROs appear technologically aware but operationally constrained: the same infrastructure gaps, capability limitations, and regulatory uncertainties that affect adoption also reinforce the error conditions identified through HFACS.

Taken together, the findings suggest that technology adoption alone is insufficient without concurrent investment in enabling conditions such as training, data governance, standardized workflows, and change management. The study's central contribution is therefore not only the identification of error mechanisms but also the conversion of HFACS from a classification tool into a feasibility-aware decision framework through SWOT integration and bounded ΔHEP reasoning. This supports more credible prioritization of what to implement first in a resource- and regulation-constrained MRO environment.

7.1 Implications for practice

The findings provide practical guidance for aligning safety improvement with digital transformation in Philippine MROs. First, technology deployment should be tied directly to

HFACS-identified error categories rather than introduced as a stand-alone innovation. AR and RFID, for instance, are likely to be most useful when embedded in targeted error-control routines and linked to documented maintenance vulnerabilities.

Second, MROs should build internal safety-technology road maps that match dominant weaknesses, such as fragmented supervision, procedural deviation, or limited traceability, to appropriate smart solutions. This can improve investment focus, reduce redundant deployments, and strengthen the feedback loop between safety diagnosis and intervention.

Third, regulators and training institutions have enabling roles. CAAP can support wider harmonization by incorporating digital-readiness and data-governance expectations into oversight, while training providers can expand curricula to include digital tool literacy, human factors awareness, and technology-assisted diagnostics. Technology vendors should likewise move toward interoperable, ecosystem-based partnerships with MROs and regulators so that digital tools reinforce, rather than bypass, existing SMS processes.

7.2 Theoretical implications

The study extends HFACS research by repositioning HFACS from a classification taxonomy toward a decision-oriented logic for maintenance intervention. HFACS remains effective for explaining what errors occur and where they propagate, but by itself, it does not indicate which controls are feasible under actual organizational and environmental conditions.

By integrating SWOT, the study adds a feasibility layer that links error pathways to the capabilities and constraints governing adoption. This combined framework explains not only why errors persist, but also why some interventions remain pilot-bound while others are more scalable. In theoretical terms, SWOT + HFACS creates a bridge between safety causation and implementation capability, allowing intervention priorities to be both mechanism-aligned and constraint-aware.

Methodologically, the study also adds bounded-impact reasoning through the ΔHEP module. Although these estimates are not empirical effect sizes, they provide a structured way to compare plausible intervention value across HFACS tiers while conditioning interpretation on readiness and implementation constraints. This makes the framework transferable to other high-reliability contexts where evidence is largely documentary and controlled experimentation is difficult.

7.3 Transferability

Although the empirical setting is the Philippine MRO, the broader pattern is relevant to other emerging aviation markets where digitalization is uneven, and safety evidence remains largely documentary. Similar barriers—variable documentation quality, weak interoperability, limited analytics readiness, workforce upskilling gaps, and regulatory uncertainty—can likewise constrain the scaling of AR-, AI-, and RFID-based solutions beyond pilot deployment.

The SWOT + HFACS logic is therefore potentially transferable because HFACS provides a stable structure for locating ermechanisms,isms and SWOT provides a practical structure for evaluating feasibility under constraint. Even so, transferability is not automatic. Replication in other settings would require recalibration of PSFs, adaptation to local reporting quality and taxonomy and adjustment to the regulatory and vendor environment that determines what constitutes feasible implementation.

7.4 Implementation challenges

The proposed technology-safety road map faces several implementation barriers. Fragmented IT systems and siloed data can weaken interoperability and limit the usefulness of AI and digital-twin applications. Inconsistent maintenance procedures and documentation quality can also reduce the effectiveness of AR guidance and RFID traceability, both of which depend on stable task structures and reliable records.

Resource limitations, particularly in budget and training capacity, may further slow workforce upskilling and long-term sustainment. Cultural resistance among experienced technicians may also reduce adoption fidelity unless change management is accompanied by strong just-culture messaging. Finally, regulatory ambiguity and uneven vendor ecosystems may delay approvals, data-governance alignment, and system integration. These barriers reinforce the need to sequence implementation with readiness-building rather than assume that technology introduction alone will improve safety performance.

7.5 Recommendations

Based on the integrated SWOT + HFACS findings and bounded *Δ*HEP estimates, Philippine MROs should adopt a staged implementation pathway that prioritizes feasible, high-value controls while building readiness for more complex tools. First, HFACS coding should be applied systematically to incident narratives, audit findings, and corrective-action records to localize dominant error mechanisms by tier. Second, technologies should be matched to those mechanisms and sequenced accordingly: AR for task-execution control, AI or analytics for fatigue- and workload-related preconditions, RFID for supervisory traceability and tool accountability, and digital twins as planning and data maturity improve.

Third, SWOT findings should be used to remove adoption barriers before large-scale rollout. This includes standardizing workflows, strengthening documentation quality and data governance, expanding training capacity, and embedding change-management and just-culture routines. Finally, implementation should be aligned early with CAAP requirements on validation, oversight, and data handling. These steps are summarized in the five-step technology–safety road map presented in Figure 6.

7.6 Limitations and directions for future research

This study has several limitations that affect scope, generalizability, and evidential strength. Access to internal materials depended on institutional permissions, producing uneven document completeness across sites and limiting the inclusion of confidential operational records. Because the evidence base was largely documentary, the analysis may also reflect self-presentation bias in how events and corrective actions were recorded. Although these risks were reduced through triangulation, structured coding, dual-coder checks, and expert

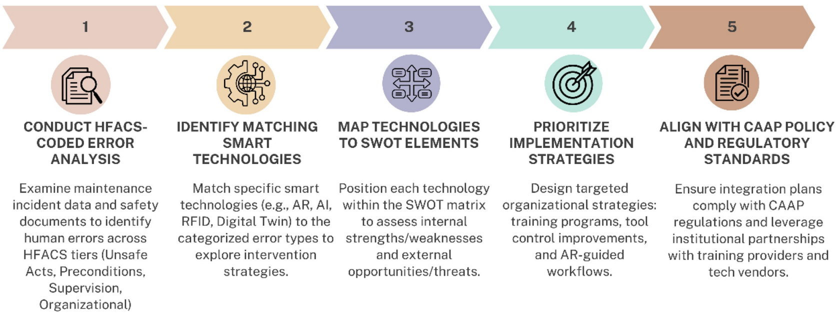

Figure 6. Five-Step Road map for Philippine MROs: Integrating HFACS-Coded Error Analysis with SWOT-Guided Smart-Technology Implementation

validation, some interpretive subjectivity remains inherent in HFACS- and SWOT-guided analysis. As a document-based multiple-case study, the work prioritizes contextual explanation rather than statistical inference and may not capture the full variability of maintenance practice across Philippine MROs.

A further limitation concerns the *Δ*HEP values reported in the study. These are scenario-based, PSF-derived bounded estimates intended to support comparative prioritization within the SWOT + HFACS framework rather than directly observed empirical effects. They should therefore not be interpreted as validated causal effect sizes. Their reliability depends on documentary quality, the plausibility of scenario assumptions, and the consistency of PSF rescoring under technology-enabled conditions.

Future research should strengthen the reliability, reproducibility, and external validity of the method through larger incident data sets and more rigorous quantitative validation. Computer simulation approaches, including Bayesian-network modeling, Monte Carlo sensitivity analysis, and digital-twin-based scenario testing, could refine PSF–HEP relationships and examine how technologies affect maintenance risk under varying conditions. Experimental and quasi-experimental studies, such as controlled task-based trials, before-and-after evaluations, or longitudinal field implementations, would also help establish more robust evidence on the actual effects of AR, AI, RFID, digital twins, and wearable systems on maintenance error reduction. The framework should also be tested in other settings, including military, UAV, and other resource-constrained maintenance environments, to assess transferability and recalibrate the *Δ*HEP logic to different regulatory, technological, and organizational contexts.

8. Conclusion

This study used an integrated HFACS–SWOT framework to examine human error and the adoption of smart technology in Philippine MROs. The findings show that maintenance risk is concentrated mainly in Unsafe Acts and Preconditions for Unsafe Acts, while supervisory and organizational factors continue to shape the conditions under which those errors occur. Procedural deviation, fatigue exposure, miscommunication, and control weaknesses remain prominent concerns. At the same time, the analysis indicates that although Philippine MROs are increasingly aware of technologies such as AR, AI, RFID, digital twins, and wearables, broader adoption remains constrained by fragmented digital infrastructure, uneven workflow standardization, limited investment in training, and regulatory uncertainty. These patterns indicate that maintenance error is best understood as a systems-level issue shaped by the interaction of task performance, organizational capability, and implementation readiness.

A key contribution of the study is the technology–error mapping supported by the quantitative module in subsection 5.5. However, the reported *Δ*HEP values should be interpreted as scenario-based, PSF-derived bounded estimates intended for comparative prioritization within the SWOT + HFACS framework, not as directly observed empirical effects. They therefore do not represent validated causal effect sizes. Rather, they provide an analytic basis for identifying which interventions may plausibly offer greater relative value under the conditions documented in this study. Within this framing, AR and selected AI applications appear more relevant for near-term task-level and precondition-related risk reduction, whereas RFID and digital twins appear more relevant for strengthening supervisory control, traceability, and organizational planning. Overall, the study suggests that the safety value of smart technologies in Philippine MROs will depend less on technological availability alone than on whether enabling conditions are developed to support credible and sustained implementation. The integrated SWOT + HFACS framework therefore contributes a transparent and context-sensitive basis for linking error diagnosis with feasibility-aware intervention prioritization in resource- and regulation-constrained maintenance settings.

Funding
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Airbus (2021), "Skywise: Predictive maintenance and fleet management", available at: https://skywise.airbus.com

Al-Rabeei, S., Alharasees, O. and Kale, U. (2022), "Human factors analysis and classification System - AHP drone model assessment", *Acta Avionica*, Vol. 24 No. 3, pp. 1-8, doi: 10.35116/aa.2022.0030.

Benzaghta, M.A., Elwalda, A., Mousa, M.M., Erkan, I. and Rahman, M. (2021), "SWOT analysis applications: an integrative literature review", *Journal of Global Business Insights*, Vol. 6 No. 1, pp. 55-73, doi: 10.5038/2640-6489.6.1.1148.

Braun, V. and Clarke, V. (2022), "Conceptual and design thinking for thematic analysis", *Qualitative Psychology*, Vol. 9 No. 1, pp. 3-26, doi: 10.1037/qup0000196.

CAAP (2022), "Annual aircraft accident and incident report 2017–2022. Civil aviation authority of the Philippines", available at: https://caap.gov.ph

Ceruti, A., Marzocca, P., Liverani, A. and Bil, C. (2018), "Maintenance in aeronautics in an industry 4.0 context: the role of AR and AM", In *TE*, IOS Press, pp. 43-50, doi: 10.3233/978-1-61499-898-3-43.

Chang, Y.C., Lee, C.Y. and Wu, C.C. (2019), "A SWOT-based approach for evaluating the technological innovation strategies of aviation MROs", *Journal of Air Transport Management*, Vol. 78, pp. 61-70, doi: 10.1016/j.jairtraman.2019.04.004.

Dalglish, S.L., Khalid, H. and McMahon, S.A. (2020), "Document analysis in health policy research: the READ approach", *Health Policy and Planning*, Vol. 35 No. 10, pp. 1424-1431, doi: 10.1093/heapol/czaa064.

Dela Peña, A. (2025), "Virtual reality in aircraft maintenance training: transforming student engagement and competency development", *Journal of Interdisciplinary Perspectives*, Vol. 3 No. 3, pp. 360-371, doi: 10.69569/jip.2025.017.

Flight Safety Foundation (2000), "Maintenance error decision aid (MEDA) user's guide", available at: https://flightsafety.org

Franciosi, C., Di Pasquale, V., Iannone, R. and Miranda, S. (2019), "A taxonomy of performance shaping factors for human reliability analysis in industrial maintenance", *Journal of Industrial Engineering and Management*, Vol. 12 No. 1, pp. 115-132, doi: 10.3926/jiem.2702.

Gao, Q., Bai, J. and Liu, Y. (2020), "Application of digital twin technology in aircraft maintenance: a review", *Journal of Aerospace Information Systems*, Vol. 17 No. 10, pp. 570-584, doi: 10.2514/1.I010841.

Harper, R. and Bliss, T. (2023), "Identification, evaluation, and causal factor determination of maintenance errors common to major U.S. certificated air carriers", *Collegiate Aviation Review International*, Vol. 41 No. 1, p. 5, doi: 10.22488/okstate.23.100230.

Hobbs, A. and Williamson, A. (2003), "Associations between errors and contributing factors in aircraft maintenance", *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 45 No. 2, pp. 186-201, doi: 10.1518/hfes.45.2.186.27240.

Hrúz, M., Bugaj, M., Novák, A., Kandera, B. and Badánik, B. (2021), "The use of UAV with infrared camera and RFID for airframe condition monitoring", *Applied Sciences*, Vol. 11 No. 9, p. 3737, doi: 10.3390/APP11093737.

Hulme, A., Stanton, N., Walker, G., Waterson, P. and Salmon, P. (2019), "Accident analysis in practice: a review of human factors analysis and classification system (HFACS) applications in the peerreviewed academic literature”, *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 63 No. 1, pp. 2173-2177, doi: 10.1177/1071181319631086.

Illankoon, P., Tretten, P. and Kumar, U. (2019), “A prospective study of maintenance deviations using HFACS-ME”, *International Journal of Industrial Ergonomics*, Vol. 74, p. 102852, doi: 10.1016/j.ergon.2019.102852.

ICAO (International Civil Aviation Organization) (2021), *Human Factors Training Manual (Doc 9683*, 3rd ed.). ICAO.

ICAO (International Civil Aviation Organization) (2023), “ICAO safety report 2023”, available at: www.icao.int/safety

Javaherikhah, A. and Sarvari, H. (2025), “Implementing building information modeling to enhance smart airport facility management: an AHP-SWOT approach”, *CivilEng*, Vol. 6 No. 1, doi: 10.3390/civileng6010015.

Johnson, J.L., Adkins, D. and Chauvin, S. (2020), “A review of the quality indicators of rigor in qualitative research”, *American Journal of Pharmaceutical Education*, Vol. 84 No. 1, p. 7120, doi: 10.5688/ajpe7120.

Kabashkin, I. and Perekrestov, V. (2024), “Ecosystem of aviation maintenance: transition from aircraft health monitoring to health management based on IoT and AI synergy”, *Applied Sciences*, Vol. 14 No. 11, p. 4394, doi: 10.3390/app14114394.

Li, W.-C. and Harris, D. (2006), “Pilot error and its relationship with higher organizational levels”, *Aviation, Space, and Environmental Medicine*, Vol. 77 No. 10, pp. 1056-1060.

Li, Y., Chen, W. and Lee, C. (2020), “Analysis of human errors in aircraft maintenance using HFACS: a study of incident reports in Asia-Pacific airlines”, *Journal of Safety Research*, Vol. 75, pp. 122-130, doi: 10.1016/j.jsr.2020.01.004.

Liangrokapart, J. and Sittiwatethanasiri, T. (2022), “Strategic direction for aviation maintenance, repair, and overhaul hub after crisis recovery”, *Asia Pacific Management Review*, Vol. 28 No. 2, pp. 166-174, doi: 10.1016/j.apmrv.2022.03.003.

Lufthansa Technik (2020), “Augmented reality in maintenance operations: use cases and trials”, available at: www.lufthansa-technik.com/ar-maintenance

Lyu, T., Song, W. and Du, K. (2019), “Human factors analysis of air traffic safety based on HFACS-BN model”, *Applied Sciences*, Vol. 9 No. 23, p. 5049, doi: 10.3390/app9235049.

Ma, H.L., Sun, Y., Chung, S. and Chan, H.K. (2022), “Tackling uncertainties in aircraft maintenance routing: a review of emerging technologies”, *Transportation Research Part E: Logistics and Transportation Review*, Vol. 164, p. 102805, doi: 10.1016/j.tre.2022.102805.

Mendes, N., Geraldo Vidal Vieira, J. and Patrícia Mano, A. (2022), “Risk management in aviation maintenance: a systematic literature review”, *Safety Science*, Vol. 153, p. 105810, doi: 10.1016/j.ssci.2022.105810.

Meng, B. and Lu, N. (2022), “A hybrid model integrating HFACS and BN for analyzing human factors in CFIT accidents”, *Aerospace*, Vol. 9 No. 11, p. 711, doi: 10.3390/aerospace9110711.

Miller, M., Mrusek, B. and Herbic, J. (2023), “Managing fatigue in aviation maintenance while promoting a human factors safety reporting system: a strategic approach to aviation safety”, *AHFE International Conference Proceedings*, pp. 595-601, doi: 10.54941/ahfe1003070.

Mohammed, T., Saoudi, T. and Younes, M. (2024), “Leveraging AI and industry 4.0 in aircraft maintenance: addressing challenges and improving efficiency”, In *2024 International Conference on Global Aeronautical Engineering and Satellite Technology (GAST)*, *IEEE*, pp. 19-24, doi: 10.1109/GAST60528.2024.10520779.

Mrusek, B. and Douglas, S.K. (2020), “From classroom to industry: human factors in aviation maintenance decision-making”, *Collegiate Aviation Review International*, Vol. 38 No. 2, pp. 72-84, doi: 10.22488/okstate.20.100218.

Nkosi, M., Gupta, K. and Mashinini, M. (2020), "Causes and impact of human error in maintenance of mechanical systems", *MATEC Web of Conferences*, Vol. 312, p. 05001, doi: 10.1051/matecconf/202031205001.

Oncu, M. and Yildiz, S. (2014), *An Analysis of Human Causal Factors in Unmanned Aerial Vehicle (UAV) Accidents*, Defense Technical Information Center, doi: 10.21236/ada620843.

Padil, H., Said, M.N. and Azizan, A. (2018), "The contributions of human factors to human error in the Malaysian aviation maintenance industry", *IOP Conference Series: Materials Science and Engineering*, Vol. 370 No. 1, p. 012035, doi: 10.1088/1757-899X/370/1/012035.

Rankin, W.L., Hibit, R., Allen, J. and Sargent, R. (2014), "Root cause analysis of maintenance errors using MEDA. Boeing technical report", available at: www.boeing.com

Reason, J. (1990), *Human Error*, Cambridge University Press, doi: 10.1017/CBO9781139062367.

Reason, J. (2020), "Maintenance-related errors: the biggest threat to aviation safety after gravity?", In *Aviation Safety*, CRC Press, doi: 10.1201/9780429070372-33.

Šajbanová, K., Čerňan, J. and Janovec, M. (2021), "Possibilities of using 3D printing technology in the production of aircraft components", *AEROjournal*, Vol. 2021 No. 2, pp. 8-14, doi: 10.26552/aer.c.2021.2.2.

Salas, R.D. and Bernal, A.F. (2021), "Readiness for predictive maintenance in commercial aviation: a SWOT analysis of implementation barriers in Asia", *Journal of Transportation Technologies*, Vol. 11 No. 3, pp. 199-209, doi: 10.4236/jtts.2021.113013.

Siddiqui, A.A. (2021), "SWOT analysis (or SWOT matrix) as a strategic planning and management technique in the healthcare industry, along with its advantages", *Biomedical Journal of Scientific and Technical Research*, Vol. 40 No. 2, pp. 31245-31249, doi: 10.26717/bjstr.2021.40.006419.

Small, A. (2020), "Human factors analysis and classification system (HFACS): as applied to Asiana airlines flight 214", *Journal of Purdue Undergraduate Research*, Vol. 10 No. 1, pp. 96-102, doi: 10.7771/2158-4052.1485.

Šváb, P., Géci, P. and Čikovský, S. (2024), "Harnessing artificial intelligence in civil aviation", In 2024, New Trends in Aviation Development (NTAD), *IEEE*, pp. 23-28, doi: 10.1109/NTAD63796.2024.10850033.

Taneja, N. and Ghosh, R. (2020), "Integrating drone-based inspections into aviation maintenance: a strategic SWOT perspective", *Journal of Aerospace Operations*, Vol. 9 No. 1, pp. 42-56, doi: 10.3233/AOP-200051.

Verhagen, W.J.C., Santos, B.F., Freeman, F., van Kessel, P., Zarouchas, D., Loutas, T., Yeun, R.C.K. and Heiets, I. (2023), "Condition-based maintenance in aviation: Challenges and opportunities", *Aerospace*, Vol. 10 No. 9, p. 762, doi: 10.3390/aerospace10090762.

Vlados, C. (2019), "On a correlative and evolutionary SWOT analysis", *Journal of Strategy and Management*, Vol. 12 No. 3, pp. 513-529, doi: 10.2139/ssrn.3389000.

Widyanti, A. and Reyhannisa, A. (2020), "Human factor analysis and classification system (HFACS) in the evaluation of outpatient medication errors", *International Journal of Technology*, Vol. 11 No. 1, pp. 69-78, doi: 10.14716/ijtech.v11i1.2278.

Wiegmann, D.A. and Shappell, S.A. (2003), *A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System*, (1st ed.) Routledge, London, doi: 10.4324/9781315263878.

Wiegmann, D.A., and Shappell, S.A. (2017), *A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System*, 1st Ed Routledge, London, doi: 10.4324/9781315263878.

Yazgan, E. and Yılmaz, A. (2019), "Prioritisation of factors contributing to human error for airworthiness management strategy with ANP", *Aircraft Engineering and Aerospace Technology*, Vol. 91 No. 1, pp. 413-425, doi: 10.1108/AEAT-11-2017-0245.

Appendix. Overview of expert clarification and feedback

To improve interpretive transparency in the document-based analysis, targeted expert clarification and optional feedback sessions were conducted with selected personnel from participating MRO-related functions. These inputs were used to clarify terminology in local reporting, resolve ambiguous incident narratives, validate borderline HFACS classifications and assess the plausibility of SWOT categorizations in the operational context. Documentary evidence remained the primary analytic basis; expert input was used only to refine interpretation and reduce ambiguity.

Table A1. Summary of expert clarification and feedback inputs

Expert role	Main purpose	Issues reviewed	Type of input provided	Use in analysis
QA officer	Clarify reporting language and compliance terminology	Ambiguous incident wording, documentation conventions	Confirmed how specific local reporting terms were used	Improved consistency of document interpretation
Safety manager	Validate whether patterns reflected routine or exceptional conditions	Occurrence narratives, SMS-related descriptions, reporting context	Clarified operational context and plausibility of interpretations	Helped distinguish recurring conditions from isolated events
Senior line supervisor	Assess practical plausibility of HFACS coding at task level	Borderline unsafe acts vs preconditions cases	Commented on likely task-level meaning of reported deviations	Supported refinement of tier placement
QA/SMS focal person	Adjudication support during coder disagreement	Borderline HFACS categories	Reviewed documentary evidence during reconciliation	Helped finalize coding decisions where needed
QA heads/ SMS officers	Optional feedback on synthesized findings	HFACS placements, SWOT categorizations, technology-readiness interpretations	Confirmed whether synthesized interpretations were operationally plausible	Strengthened transparency of the analytic process

Corresponding author
Arthur Conlas Dela Peña can be contacted at: artair248@gmail.com