

Original Article

Smart Wearables for Safer and Traceable Aircraft Maintenance: An Implementation, Safety, and Traceability Framework

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Abstract. Aircraft maintenance, repair, and overhaul (MRO) is undergoing rapid digital transformation. However, the implementation of smart wearables in regulated maintenance environments remains insufficiently specified, particularly regarding safety, documentation control, and audit-grade traceability. This study aims to develop and apply an integrated implementation-safety-traceability framework to evaluate the deployment of smart wearables in Philippine MRO facilities. Using a retrospective document-based case study design, the study analyzed controlled organizational records, operational logs, quality and safety documents, and traceability evidence without direct human participation. Findings show that the implementation of wearables is primarily a socio-technical governance challenge rather than a simple technology adoption issue. Determinant salience was strongest in workflow fit, interoperability, inner-setting readiness, and implementation-process discipline. Implementation outcomes were conditional: feasibility depended on infrastructure reliability and integration stability; fidelity depended on controlled workflow execution and documentation continuity; penetration remained limited to selected task families; and sustainability was strongest where wearables were embedded in procedures and support routines. Safety analysis showed that documentation and sign-off deviations coexisted with safe recovery behaviors when escalation pathways and continuity controls were present. Regulatory-traceability fit was strongest where version linkage, sign-off integrity, and cross-system evidence continuity were preserved. The proposed Wearable MRO Readiness Index indicated moderate overall readiness, supporting phased, compliance-compatible scale-up rather than immediate enterprise-wide rollout. The study offers a practical framework for MRO managers, regulators, and quality assurance personnel to assess readiness, identify risks, and guide the responsible implementation of wearable technologies.

Keywords: Aircraft maintenance; Implementation framework; Safety; Smart wearables; Traceability

Aircraft maintenance, repair, and overhaul (MRO) is increasingly shaped by digital transformation as operators seek faster turnaround, stronger documentation control, improved reliability, and better integration of maintenance data across operational and quality systems (Alomar & Yatskiv, 2023; Karakilic

et al., 2023). This issue is relevant globally and in the Philippines, where maintenance organizations must modernize work processes while preserving airworthiness, safety assurance, and regulatory compliance. Within this transition, smart wearables and related extended-reality tools have attracted attention because they can support hands-free access to procedures, task guidance, remote assistance, and real-time documentation at the point of work. Ceruti et al. (2019) highlighted the role of augmented reality in aeronautical maintenance, while Malta et al. (2023) reviewed its development and future use in maintenance contexts. However, wearable value depends not only on device capability but also on workflow fit, interface usability, connectivity stability, and integration with existing maintenance systems, as shown in broader studies on augmented-reality guidance and head-mounted displays (Eswaran et al., 2023; Fang et al., 2023).

This issue becomes more critical in regulated MRO environments, where work is procedure-bound, time-sensitive, and documentation-intensive. In such settings, a wearable system that improves information access but weakens revision control, sign-off integrity, or evidence continuity may create operational and compliance risks rather than meaningful gains. Aircraft maintenance is a high-reliability and traceability-intensive activity in which documentation quality, certification accuracy, and procedural compliance directly affect continuing airworthiness and safety. Abbas and Khare (2024) showed how final inspection and certification errors can affect the release of aircraft components, while Clare and Kourousis (2021) emphasized the importance of learning from maintenance and continuing airworthiness incidents. Despite these developments, there is limited operational guidance on how wearable-enabled aircraft maintenance workflows should preserve version alignment, sign-off accountability, audit retrievability, and cross-system evidence continuity in practice.

Existing research also leaves an important practical gap. Wearable technology studies remain concentrated in healthcare and general industrial applications, with limited attention to maintenance-specific deployment in regulated aviation environments. Lončar-Turukalo et al. (2019) mapped research trends and barriers in connected wearable technologies, while Stan et al. (2025) identified continuing challenges in wearable health and telemonitoring systems. In aviation maintenance, digitalization studies increasingly recognize the importance of traceability and lifecycle data integration, but they provide limited guidance for governing wearable-supported workflows. Moenck et al. (2024) discussed integration challenges in digital aircraft production and MRO, while Susanin and Kabashkin (2025) emphasized reliability-centered lifecycle modification. These studies support the need to treat the deployment of smart wearables not merely as technology adoption but as a socio-technical implementation and governance problem.

In addition to these practical limitations, there is also a theoretical gap. Much of the technology adoption literature relies on models such as the Technology Acceptance Model, which explains perceived usefulness and ease of use but is less suited to the organizational complexity of regulated MRO implementation (Gupta et al., 2022; Marikyan et al., 2023). Wearable deployment in aircraft maintenance depends on broader conditions, including leadership support, infrastructure readiness, workflow redesign, interoperability, documentation governance, and implementation discipline. These factors are better addressed through implementation science perspectives. Damschroder et al. (2022) updated the Consolidated Framework for Implementation Research to examine implementation determinants; Proctor et al. (2023) clarified implementation outcomes, including feasibility, fidelity, penetration, and sustainability; and Reardon et al. (2025) provided practical guidance for applying the CFIR in implementation research. However, implementation outcomes, safety implications, and regulatory traceability are often examined separately, even though wearable-supported workflows may affect all three simultaneously.

Accordingly, this study develops and applies an integrated implementation-safety-traceability framework to evaluate the deployment of smart wearables in Philippine MRO facilities. Using documentary and archival evidence rather than direct human-participant methods, the study examines the determinants shaping wearable operationalization, the implementation outcomes reflected in records and logs, safety-related deviations and adaptations, and the traceability conditions required for compliance-compatible deployment. The framework links four analytic layers: implementation determinants, implementation outcomes, safety implications, and regulatory-traceability fit. The study is significant because it offers MRO managers, regulators, engineers, and quality assurance personnel a practical basis for assessing readiness, identifying deployment risks, strengthening documentation control, and supporting phased, compliance-compatible implementation of smart wearables in Philippine maintenance facilities and similar regulated aviation contexts.

Conceptual Framework

This study adopts the WSIT-MRO framework as an integrated lens for evaluating the deployment of smart wearables in regulated aircraft maintenance. Figure 1 presents the framework used in the study. It organizes the analysis into four linked layers: implementation determinants, implementation outcomes, safety outcomes, adaptation patterns, and regulatory-traceability fit. The first layer identifies implementation conditions such as workflow fit, readiness, governance, infrastructure, and implementation process. The second layer examines implementation outcomes using record-based indicators of feasibility, fidelity, penetration, cost burden, and sustainability. The third layer interprets safety-related deviations and adaptive responses through a combined Safety-I/Safety-II and HFACS-informed lens. The fourth layer assesses regulatory-traceability fit through auditability, sign-off integrity, revision control, evidence continuity, and data provenance. Together, these layers connect documentary and archival evidence—such as controlled procedures, quality assurance records, audit findings, implementation artifacts, and system logs—to practical deployment decisions. The framework, therefore, provides a structured basis for assessing readiness, identifying risks, preserving compliance, and supporting the phased scale-up of smart wearables in regulated MRO settings.

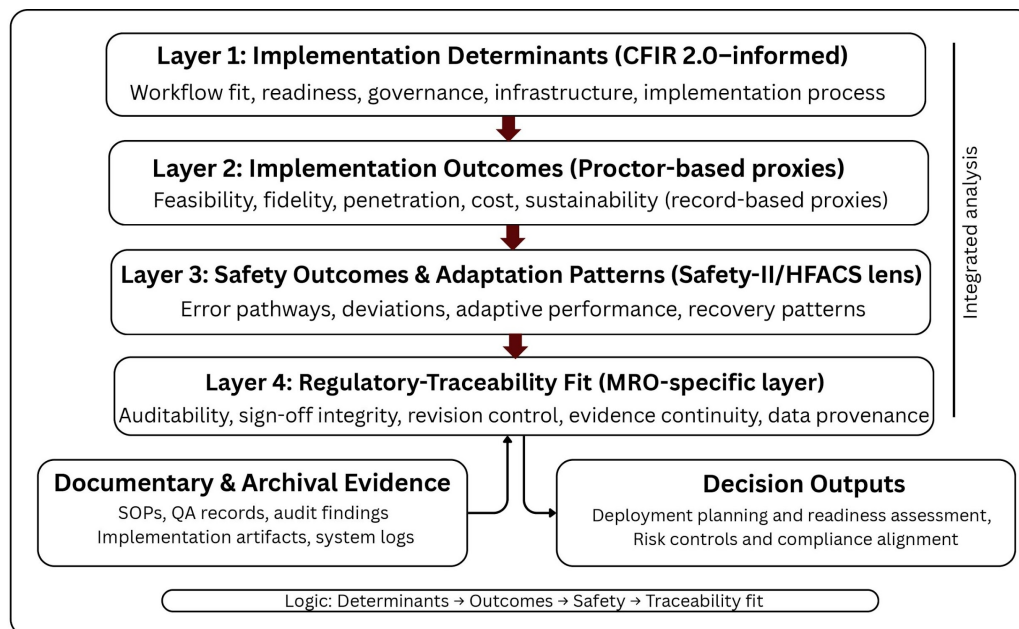


Figure 1. WSIT-MRO Framework for Smart Wearable Implementation in Regulated Aircraft Maintenance

Methodology

Research Design

This study employed a retrospective, multi-source document and archival case study design to evaluate the operationalization of smart wearables in regulated aircraft maintenance. The study is empirical because it analyzes actual organizational records and documented operational evidence; however, it does not involve interviews, surveys, observations, experiments with individuals, or any form of direct human participation. This design was appropriate because wearable deployment in aircraft maintenance is context-dependent, implementation-intensive, and embedded in regulated work systems where compliance, airworthiness assurance, and evidence continuity depend on documented processes and auditable records (Wohlin & Rainer, 2022).

A case study approach was selected because the study examines how smart wearables are implemented within bounded maintenance workflows rather than testing the device as an isolated technology. In regulated MRO settings, operational practices are reflected in controlled procedures, quality records, audit trails, and system-generated logs, making documentary and archival evidence suitable for reconstructing implementation conditions, safety implications, and traceability performance. This approach is consistent with the audit-oriented nature of aircraft maintenance, where task execution, sign-off integrity, safety assurance, and quality management are commonly documented through standardized records (Insley & Turkoglu, 2020; Moilanen et al., 2022).

Controlled organizational records served as the primary evidence base because they strengthen analytic credibility through auditability, traceability, and standardization. Unlike informal accounts, controlled records usually contain document ownership, revision histories, timestamps, approval pathways, and system-of-record references, allowing the analysis to verify whether wearable-supported workflows preserved procedural control and evidence continuity. As summarized in Table 1, which presents the indicators used in the study, the WSIT-MRO framework was operationalized through document- and log-based indicators covering implementation determinants, implementation outcomes, safety implications, and regulatory-traceability fit. Detailed descriptions of the specific data sources, inclusion criteria, and extraction procedures are presented in the Data Collection and Extraction section.

Table 1. *Summary of WSIT-MRO Operationalization*

Framework Layer	Main Focus	Typical Evidence Source	Analytic Approach
Implementation Determinants	Workflow fit, readiness, governance, process	SOPs, rollout records, integration logs	CFIR-informed coding
Implementation Outcomes	Feasibility, fidelity, penetration, sustainability	Workflow logs, QA records, support records	Documentary proxy analysis
Safety Implications	Deviations and adaptive responses	NCRs, audit findings, incident narratives	Safety-I/Safety-II and HFACS-informed coding
Regulatory-Traceability Fit	Version control, sign-off integrity, evidence continuity	Task cards, audit trails, e-signature and QA records	Traceability assessment

Case Context and Boundary

This study adopted a single embedded case study design focused on one anonymized Philippine MRO facility that had initiated or piloted smart wearable-enabled maintenance workflows within a regulated aircraft maintenance environment. A single-case design was appropriate because the study aimed to examine the operationalization of smart wearables in depth within a bounded, compliance-intensive setting rather than compare multiple facilities statistically. The embedded units of analysis were selected workflow or task-family areas within the facility, allowing the study to examine variation across maintenance activities while preserving the coherence of one organizational case (Rashid et al., 2019; Wohlin & Rainer, 2022).

The case was selected using defined inclusion criteria. The facility had to: (a) operate within a regulated aircraft maintenance context; (b) have initiated, piloted, integrated, or formally evaluated smart wearable-supported workflows; (c) maintain auditable records related to procedure execution, sign-off, quality assurance, safety, or system use; (d) provide sufficient documentary evidence across implementation stages; and (e) demonstrate documented compliance controls, such as controlled procedures, revision histories, audit trails, quality records, or corrective-action evidence. These criteria ensured that the case could support a credible document-based reconstruction of the determinants of implementation, safety implications, and regulatory-traceability conditions.

The unit of analysis was the workflow-level operationalization of smart wearables rather than the wearable device itself. This boundary was necessary because the safety and compliance value of wearables in MRO depends less on the physical device and more on how the technology changes task execution, documentation control, sign-off accountability, audit retrieval, and cross-system evidence continuity. Workflow-level analysis was therefore more appropriate for assessing operational impact, regulatory traceability, and implementation readiness in maintenance activities such as e-task card execution, inspection sign-off, troubleshooting or remote assistance, and parts identification or trace capture (Alomar & Yatskiv, 2023; Karakilic et al., 2023).

The analysis covered a retrospective 12–36-month period, depending on the availability and completeness of auditable records. This timeframe was selected because it was sufficient to capture the main implementation lifecycle: pre-implementation preparation, pilot or deployment activity, and post-implementation stabilization or discontinuation. A shorter period may not adequately show whether wearable-supported workflows were embedded into procedures, sustained through routine use, or associated with recurring safety, quality, or traceability issues. The selected window, therefore, supported a more complete assessment of feasibility, fidelity, penetration, sustainability, and evidence continuity.

The study excluded technician perception data, interviews, surveys, and direct observations. This exclusion was intentional and consistent with the documentary and archival design. The focus was on objective, audit-based evidence rather than self-reported experience, thereby reducing subjective bias and strengthening traceability to

controlled records. Accordingly, the study was limited to wearable-supported workflows with sufficient auditable evidence, including controlled procedures, task cards, sign-off or e-signature logs, document-control records, QA NCR/CAPA files, audit trails, and IT or service logs. This boundary supports analytical transferability while avoiding overgeneralization beyond the documented case context (Insley & Turkoglu, 2020; Moilanen et al., 2022).

Data Sources and Extraction

Consistent with the retrospective documentary and archival design, data were drawn from controlled institutional records and system-generated documents related to smart wearable-supported maintenance workflows. A purposive documentary sampling strategy was used to select records based on relevance to the WSIT-MRO framework, traceability to an official source, and usefulness for audit-based analysis. This approach was appropriate because the study relied on verifiable organizational evidence rather than self-reported accounts (Moilanen et al., 2022; Nowell et al., 2017).

The selection process followed three steps. First, the in-scope workflow areas were identified, including e-task card execution, inspection sign-off, troubleshooting or remote assistance, and parts identification or trace capture. Second, relevant records were retrieved from document-control files, quality assurance records, audit records, implementation files, operational system logs, and technical integration documents. Third, each record was screened for authenticity, relevance to wearable-enabled workflows, inclusion within the study period, traceability to an issuing unit or system of record, and completeness for coding. Records were excluded if they were duplicated, outside the case boundary, unrelated to wearable-supported workflows, incomplete beyond reliable interpretation, or not traceable to an official source.

The included evidence streams covered regulatory and procedural documents, implementation artifacts, operational system records, quality and safety records, audit and traceability evidence, and technical integration documentation. As summarized in Table 2, these sources supported the analysis of implementation determinants, implementation outcome proxies, safety and adaptation patterns, and regulatory-traceability fit. To strengthen transparency, each included record was logged by document type, source, date or coverage period, workflow relevance, controlled status, revision history where available, and reason for inclusion. Missingness, redaction, ambiguity, and duplicate removal were also documented to avoid over-interpretation.

Data extraction used a structured template aligned with the WSIT-MRO framework. For each record, evidence was extracted on implementation determinants, implementation outcomes, safety-related deviations or adaptations, and traceability indicators. Coding notes and rule refinements were recorded in an audit trail to preserve a clear chain from source document to analytic interpretation (Moilanen et al., 2022; Nowell et al., 2017; O'Brien et al., 2014).

Table 2. *Data Sources and Analytic Purpose*

Data Source Category	Examples	Time Period	Inclusion Criteria	Analytic Purpose	Framework Layer Supported
Regulatory and Procedural Documents	Controlled SOPs, work instructions, task-card rules, revision histories, document control logs	Study window (e.g., 12–36 months) + last pre-window revision for baseline	Controlled status identifiable; revision lineage available; directly governs in-scope workflows	Establish baseline process + required evidence; assess traceability fit (version control, sign-off rules)	CFIR (process/governance), Traceability fit
Implementation Artifacts	Rollout memos, training plans/materials, deployment registers, pilot checklists, troubleshooting/issue logs		Explicit linkage to wearable initiative (project code, sponsor, device/workflow identifiers)	Code determinants (planning, readiness, support), map implementation timeline and governance	CFIR determinants
Operational System Records	Timestamp logs, completion logs, sync logs, device/app usage traces, digital sign-off/e-signature records	During and post deployment; baseline logs if available	System-generated or exported with metadata; fields sufficient for proxy measures	Proxy implementation outcomes (feasibility, fidelity, penetration, sustainability)	Proctor outcomes (proxied)

QA and Safety Records	NCRs/nonconformities, deviations, CAPA, repeat-finding registers, discrepancy narratives	Full window; include pre-window baseline summary if available	Record includes date, classification, workflow/task link, and narrative/descriptor fields	signals) Code safety pathways and adaptations; identify recurring patterns and control breakdowns	Safety-II/HFACS layer; also links to outcomes
Audit/Traceability Evidence	Internal audit findings, compliance checklists, documentation completeness reports, corrective action verification notes	Audit cycles overlapping the window	Auditable reference to evidence set (document IDs, sample lists, closure verification)	Evaluate auditability, completeness, and evidence continuity; triangulate traceability fit	Traceability fit; Proctor (sustainability signals)
Technical System Integration Documentation	Architecture notes, interface mappings, change requests, downtime/availability reports, integration incident tickets	During build/pilot + stabilization	References wearable system and target e-MRO/QA systems; includes incident/change metadata	Identify interoperability constraints; support feasibility/fidelity interpretation	CFIR (compatibility/readiness), Proctor (feasibility/fidelity)

Data Extraction Protocol

A structured data-extraction protocol was used to ensure consistent, transparent, and reproducible handling of documentary and archival evidence. The protocol was guided by the WSIT-MRO framework and followed a standardized extraction template that covered the source document, issuing unit or system of record, date or coverage period, workflow relevance, controlled-document status, revision lineage, where available, evidence summary, and data-quality notes. Highly detailed template fields and coding tags were retained in Appendix A to keep the main methodology concise while preserving methodological transparency.

Extraction proceeded in four stages. First, each record was screened against the study's inclusion criteria and logged in an audit trail. Second, relevant evidence was extracted and linked to one or more WSIT-MRO domains: implementation determinants, implementation outcome proxies, safety-related deviations or adaptations, and regulatory-traceability indicators. Third, records were coded using predefined decision rules, with short analytic memos written for ambiguous or non-obvious classifications. Fourth, coding decisions, exclusions, missing data, redactions, and rule refinements were documented to maintain a clear chain from source evidence to interpretation.

To strengthen coding consistency, the codebook was developed before full extraction and tested on an initial subset of records. Coding rules were then refined before applying the protocol to the full dataset. Where dual review was feasible, a second reviewer independently checked a subset of extracted records to assess the consistency of construct assignment. Disagreements were resolved through discussion, comparison with the codebook, and revision of decision rules where needed. Where only one coder was available, consistency was supported through code-recoding checking, structured memoing, and periodic comparison of coded records against the extraction protocol. Ambiguous evidence was classified as partial or uncertain rather than forced into a definitive category. These procedures strengthened credibility, dependability, and confirmability in the documentary analysis (Moilanen et al., 2022; Nowell et al., 2017; O'Brien et al., 2014).

Data Analysis

Data analysis followed a deductive-inductive coding approach guided by the WSIT-MRO framework. The initial coding structure was developed deductively from the framework's four layers: implementation determinants, implementation outcomes, safety implications, and regulatory-traceability fit. Implementation determinants were coded using adapted CFIR 2.0 domains, including intervention characteristics, outer setting, inner setting, individuals or roles, and implementation process (Damschroder et al., 2022; Reardon et al., 2025). To ensure coding consistency, a codebook was prepared before full analysis and tested on an initial subset of records. The codebook defined each construct, inclusion and exclusion rules, typical evidence sources, and example indicators. After pilot coding, unclear or overlapping categories were refined. Where dual review was feasible, a second reviewer checked a subset of coded records, and disagreements were resolved through discussion and reference to the codebook. Where only one coder was available, consistency was supported through code-recode checks, analytic memoing, and periodic review of coded records against the extraction protocol. Ambiguous evidence was coded

as partial or uncertain rather than forced into fixed categories (Moilanen et al., 2022; Nowell et al., 2017).

Inductive sub-codes were added when recurring MRO-specific factors appeared in the records, such as document-control constraints, connectivity gaps, tooling discipline, shift handover issues, and system-of-record limitations. These sub-codes were reviewed for recurrence and evidentiary support, then linked back to the closest CFIR construct or WSIT-MRO layer. This allowed context-specific findings to refine interpretation while preserving alignment with the overall framework (Fridberg et al., 2021; Li et al., 2025). Implementation outcomes were analyzed using document- and log-based indicators. Feasibility was assessed through downtime, synchronization issues, workarounds, and support incidents; fidelity through workflow completion, documentation consistency, and deviations from controlled procedures; penetration through workflow coverage; and sustainability through continued procedural use, training evidence, support routines, and recurring operational records (Akiba et al., 2022; Proctor et al., 2023; Smith & Hasan, 2020).

Safety evidence was analyzed using a combined Safety-I/Safety-II and HFACS-informed approach. HFACS supported classification of deviations, preconditions, supervisory factors, and organizational influences, while Safety-II helped interpret adaptive responses and recovery actions that preserved safe task execution under operational variability (Illankoon et al., 2019; Lima Brugnara et al., 2023). Regulatory-traceability fit was assessed through documentation completeness, version integrity, action traceability, sign-off accountability, audit retrievability, and cross-system evidence continuity (Kabashkin, 2024; Meissner et al., 2025). Finally, findings were integrated through cross-layer comparison. Implementation determinants were linked to outcome patterns, safety deviations or adaptations, and traceability conditions. This integration informed the Wearable MRO Readiness Index and supported practical recommendations for phased, compliance-compatible smart wearable deployment.

Proctor Implementation Outcome Operationalization

Implementation outcomes were operationalized using record-based indicators aligned with Proctor's implementation outcome logic. Because the study used a documentary and archival design, outcomes were assessed only when supported by verifiable organizational records, system logs, controlled documents, or formal evaluation artifacts. This approach allowed the study to distinguish directly observable outcomes from proxy-based outcomes while keeping the indicator logic explicit and auditable (Akiba et al., 2022; Proctor et al., 2023; Smith & Hasan, 2020).

The main implementation outcomes were mapped as follows. Feasibility was assessed through documented evidence of downtime, synchronization failure, connectivity or battery issues, support incidents, and workaround frequency. Fidelity was examined through workflow completion records, documentation consistency, sign-off completeness, and deviations from controlled procedures. Penetration was assessed through the number and type of workflow areas using wearable-supported processes, such as e-task execution, inspection sign-off, troubleshooting or remote assistance, and parts identification or trace capture. Sustainability was inferred from continued use across the study period, incorporation into controlled procedures, recurring training or support routines, and evidence of continued governance after initial deployment. Where available, cost burden was examined through records of device support, integration effort, downtime management, maintenance requirements, and related resource demands.

Outcomes that inherently require direct user perception, such as acceptability, satisfaction, or perceived appropriateness, were excluded unless they appeared in formal documentary evidence, such as approved pilot evaluation reports, usability summaries, or signed acceptance records. This exclusion was intentional and consistent with the study's non-human-participant, audit-based design. Limiting the analysis to verifiable documentary evidence reduced reliance on subjective self-report, preserved methodological consistency, and strengthened traceability between the source records and the study's findings. Thus, implementation outcome claims were made only when supported by auditable evidence rather than assumptions about user experience or informal practice.

Safety Analysis Using Safety-II and HFACS

Safety-related records were analyzed using an integrated Safety-II and HFACS-informed approach. HFACS was first used to classify documented deviations, nonconformities, and safety-related events into structured categories, including unsafe acts, preconditions, supervisory factors, and organizational influences. This provided a consistent taxonomy for identifying how wearable-supported workflows were associated with documentation

errors, sign-off delays, procedural deviations, workflow interruptions, or organizational control weaknesses. This approach is consistent with aviation maintenance studies that use HFACS to examine maintenance deviations and contributory factors before they develop into more serious safety events (Illankoon et al., 2019). Safety-II analysis was then applied to the same set of records to identify adaptive responses, recovery actions, and resilience mechanisms. These included escalation to supervisors or IT support, use of continuity procedures during connectivity loss, correction of incomplete documentation, and other actions that helped preserve safe task progression under operational variability. This avoided a failure-only interpretation and allowed the analysis to capture how personnel and systems adjusted to maintain safety despite technical or procedural disruptions (Lima Brugnara et al., 2023).

Findings from HFACS and Safety-II were integrated through cross-coding. Each safety-related record was examined not only for its contributory factor under HFACS but also for the presence or absence of adaptive recovery under Safety-II. For example, a delayed sign-off could be coded under HFACS as a documentation or supervisory-control issue, while the corresponding recovery action could be coded under Safety-II as a successful adaptation if the record showed escalation, correction, and preservation of evidence continuity. Conversely, a workaround was interpreted as safety-supportive only when it preserved procedural control and traceability; it was treated as risk-amplifying when it bypassed required documentation, fragmented evidence, or weakened sign-off accountability. This integrated analysis produced a unified interpretation of safety outcomes by linking error pathways with recovery capacity. HFACS identified where and why control weaknesses occurred, while Safety-II explained whether the system was able to absorb, recover from, or learn from those weaknesses. Together, the two approaches supported a balanced assessment of wearable-related safety by examining both deviations and adaptive performance in regulated aircraft maintenance workflows.

Regulatory–Traceability Fit Assessment

Regulatory–traceability fit was assessed using an evidence-based rubric covering six dimensions: documentation completeness, revision/version integrity, action traceability, sign-off accountability, audit retrievability, and cross-system evidence continuity. Each dimension was scored on a 0–2 scale: 0 = absent or non-compliant evidence, 1 = partial or fragile evidence, and 2 = complete and robust evidence. This simple three-level scale was used because it aligns with audit-oriented regulatory logic in aircraft maintenance, where evidence is commonly judged as absent, partially adequate, or adequate for compliance verification. It also supports transparent scoring when documentary evidence varies in completeness across workflow areas (Meissner et al., 2025; Moilanen et al., 2022).

The scoring relied on verifiable indicators such as controlled-document lineage, current procedure linkage, e-signature or sign-off traces, timestamps, cross-system identifiers, closed-loop corrective-action evidence, and audit-sampling retrievability. Scores were summarized using the mean dimension score to describe overall traceability strength, while a minimum-rule flag was applied as a safeguard: if any dimension scored 0, the workflow was classified as traceability-critical regardless of the mean. This rule reflects the weakest-link nature of regulated maintenance evidence chains, where one missing element – such as absent sign-off accountability or broken revision control – can compromise audit readiness and compliance confidence (Kabashkin, 2024; Meissner et al., 2025).

In practical terms, higher scores indicated stronger readiness for continued or expanded wearable deployment because the workflow preserved auditable evidence, accountability, and documentation continuity. Partial scores indicated that deployment could proceed only with safeguards, such as corrective actions, additional controls, or limited pilot use. Any traceability-critical result indicated that scale-up should be deferred until the missing compliance evidence was restored. Thus, the scoring results were used not as a regulatory certification decision, but as a structured basis for identifying traceability risks, prioritizing remediation, and supporting phased, compliance-compatible implementation of smart wearables in MRO workflows.

WMRI: Wearable MRO Readiness Index

The Wearable MRO Readiness Index (WMRI) was proposed as a structured facility-level measure for translating documentary and archival evidence into an overall readiness profile for smart wearable deployment. The index consists of six readiness dimensions: technical integration readiness, documentation governance maturity, infrastructure reliability, training and process readiness, safety governance readiness, and regulatory-traceability readiness. These dimensions represent the key technical, organizational, procedural, safety, and compliance

conditions needed for wearable operationalization in regulated aircraft maintenance (Flamini & Naldi, 2022; Abdullah & Al-Ahmari, 2025). Each dimension was assessed using verifiable evidence from controlled documents, system logs, quality records, training artifacts, audit trails, and technical integration records. A three-point scoring scale was applied: 0 = not evident or inadequate, 1 = partially evident or inconsistent, and 2 = clearly evident and operationally supported. When a dimension contained several indicators, the indicator scores were averaged to produce the dimension score. Each dimension score was then normalized to a 0–1 scale to allow consistent comparison across readiness areas.

The overall WMRI was constructed using an equal-weight composite approach, with the six normalized dimension scores averaged to produce one readiness value. Equal weighting was used because the study is exploratory and document-based, with no empirical or regulatory basis for assigning greater weight to one readiness dimension over another. This approach improves transparency and replicability while allowing future applications to use expert-derived or regulator-defined weights when properly justified. Any alternative weighting scheme should be reported and tested through sensitivity analysis because composite index results may change depending on weighting and normalization choices (Kelemen et al., 2024; Shi & Land, 2021). The WMRI was used as a decision-support measure rather than a certification tool. It provides a practical basis for identifying readiness gaps, comparing workflow-level preparedness, prioritizing corrective actions, and supporting phased, compliance-compatible implementation of smart wearables in MRO workflows.

Scoring Method

The WMRI was computed by normalizing each readiness dimension to a 0–1 scale and aggregating the six normalized dimension scores using an equal-weight composite approach. Equal weighting was used for transparency, as the study is exploratory and document-based, with no empirical or regulatory basis to assign greater weight to one readiness dimension over another. Alternative expert-derived or regulator-defined weights may be used in future applications, provided that the weighting rationale is documented and tested through sensitivity analysis, since composite scores may vary depending on normalization and weighting choices (Kelemen et al., 2024; Shi & Land, 2021).

For practical use, the final WMRI score was interpreted using three readiness bands: 0.00–0.39 = low readiness, 0.40–0.69 = moderate readiness, and 0.70–1.00 = high readiness. Low readiness indicates that deployment of smart wearables should be deferred until major technical, procedural, safety, or traceability gaps are corrected. Moderate readiness indicates conditional readiness and supports limited or phased deployment with safeguards, monitoring, and corrective actions. High readiness indicates stronger suitability for broader deployment, provided that safety controls, documentation governance, and evidence continuity remain stable. These bands convert the WMRI from a numerical score into an actionable decision-support tool for identifying readiness gaps, prioritizing remediation, and guiding phased implementation rather than serving as a formal certification or regulatory approval measure (Verreynne et al., 2025; Vilarinho et al., 2026).

Interpretation Bands

The WMRI readiness bands were used to translate the composite score into practical deployment decisions. The bands were defined as low readiness (scores of 0.00–0.39), moderate readiness (scores of 0.40–0.69), and high readiness (scores of 0.70–1.00). These cutoffs were adopted as pragmatic stage-based thresholds, consistent with readiness and maturity-index logic, in which organizations are grouped into levels of preparedness to guide improvement planning and implementation decisions (Verreynne et al., 2025). Because such thresholds can influence interpretation, they are treated as transparent decision rules that may be recalibrated in future applications using expert judgment, regulatory expectations, or empirical benchmarking (Kelemen et al., 2024; Vilarinho et al., 2026). In application, low readiness indicates that wearable deployment should be deferred until major technical, procedural, safety, or traceability gaps are corrected. Moderate readiness indicates conditional readiness and supports limited pilot use or phased expansion with safeguards, monitoring, and corrective actions. High readiness indicates suitability for broader deployment, provided that documentation governance, sign-off integrity, safety controls, and auditability remain stable. Thus, the interpretation bands convert the WMRI score into actionable implementation guidance by identifying whether a workflow requires remediation, controlled pilot expansion, or broader scale-up.

Rigor and Trustworthiness/Quality Assurance

Rigor was maintained through a versioned codebook, audit trail, triangulation, validation checks, and

conservative interpretation of ambiguous evidence. Before full analysis, the codebook was pilot-tested on an initial subset of records and refined to clarify construct definitions, inclusion rules, proxy indicators, and traceability-scoring criteria. During analysis, an independent coding check or peer debriefing was conducted on a purposive validation subset of records representing the major data-source categories and workflow areas. The review focused on construct assignment, evidence sufficiency, proxy interpretation, and consistency of traceability scoring. Disagreements were resolved by referring to the codebook, rechecking the source evidence, and revising decision rules when needed. All refinements were logged and applied consistently across the dataset.

Triangulation across procedures, implementation artifacts, operational logs, quality and safety records, and audit evidence strengthened credibility by reducing reliance on a single source. The audit trail improved dependability and confirmability by documenting inclusion decisions, coding changes, proxy-mapping rationale, missing data, and classification uncertainties. Sensitivity checks supported the robustness of readiness and traceability scores by examining whether interpretations changed under alternative scoring assumptions. Where only one coder was available, single-coder bias was mitigated through code-recode checking, structured memoing, and periodic review against the extraction protocol. Ambiguous evidence was classified as partial or uncertain rather than forced into definitive categories. Together, these procedures improved consistency, reduced interpretive bias, and preserved a transparent link between source records and study findings (Johnson et al., 2020; Moilanen et al., 2022; Naeem et al., 2023; Nowell et al., 2017).

Ethical Considerations

This study involved no direct human participants and did not use interviews, surveys, observations, or experiments with individuals. It relied solely on retrospective institutional documents and archival operational records. To protect confidentiality, all facility, personnel, aircraft, and operational identifiers were removed or masked before analysis, including names, signatures, employee numbers, tail numbers, work-order references, timestamps, and system-specific identifiers. Data were stored in password-protected and access-controlled digital files, with access limited to the authorized researcher/research team. Where available, encrypted storage was used, and working files were separated from any source-identification records. Safety, quality, and compliance documents were reported only in aggregated or non-identifying form to prevent disclosure of operational vulnerabilities.

Results and Discussion

Implementation Context, Determinant Salience, and Implementation Outcomes

The case involved an anonymized Philippine MRO setting operating in a regulated, documentation-intensive environment, where smart wearables were used within bounded workflows such as e-task execution, inspection/sign-off, troubleshooting or remote assistance, and parts identification or trace capture. The evidence indicates early operationalization rather than full facility-wide institutionalization, suggesting that wearables had progressed beyond conceptual exploration but remained concentrated within selected workflow families. This bounded deployment is analytically important because it shows that wearable integration in MRO does not typically begin as an enterprise-wide transformation; rather, it emerges through workflow-specific applications where documentation continuity, procedural control, and compliance demands are already high.

Across the documentary record, the most salient determinants of implementation were workflow fit, inner-setting readiness, and implementation process quality. Wearable operationalization depended less on device availability than on whether the system aligned with e-MRO workflow logic, avoided duplicate entry, preserved documentation control, and was supported by clear planning, training, escalation, and issue-management routines. As shown in Table 3, determinant salience was strongest in e-task/procedure execution and inspection/sign-off, where wearable-supported work had to remain tightly aligned with controlled procedures and auditable evidence chains. Salience was lower, though still visible, in troubleshooting/remote assist and parts identification/trace capture, where the pressures for documentation continuity were less direct. These findings indicate that the deployment of wearables in MRO is primarily a socio-technical governance challenge rather than a straightforward adoption problem.

Implementation outcomes reflected the same pattern. Feasibility was conditional rather than absolute, with evidence of downtime, sync failures, battery or connectivity instability, and unresolved support incidents showing that wearable-supported workflows remained dependent on infrastructure reliability and integration stability. Fidelity was stronger where workflow sequence and record completeness were preserved, but weaker where

bypassed steps, incomplete entries, and QA-linked documentation inconsistencies appeared. Penetration remained limited to selected workflows rather than full operational saturation, while sustainability signals were strongest where wearable use had been embedded in SOPs, repeat training, and support routines. Overall, implementation performance depended not only on technical functionality but also on the organization's capacity to absorb the procedural, support, and governance burden of maintaining wearables in a traceability-intensive MRO setting.

These findings are consistent with research on digital maintenance, which shows that the value of paperless and connected MRO systems depends on workflow integration, documentation control, and operational fit rather than on technology alone (Alomar & Yatskiv, 2023; Karakilic et al., 2023). They also extend implementation research by showing that, in a regulated MRO context, feasibility, fidelity, and bounded penetration are shaped less by adoption attitudes than by readiness, interoperability, and implementation-process discipline, in line with broader CFIR and implementation-outcomes scholarship (Damschroder et al., 2022; Proctor et al., 2023).

Table 3. *Determinant Salience and Implementation Implications Across Wearable-Supported Workflow Areas*

Workflow Area	Dominant Determinant Pattern	Implementation Implication
E-Task/Procedure Execution	Strong workflow-fit, documentation-control, and process-governance demands	Highest operational relevance but also highest need for controlled integration
Inspection/Sign-Off	Strong readiness, traceability, and sign-off integrity requirements	Suitable for expansion only where authorization and evidence continuity are stable
Troubleshooting/Remote Assist	Moderate interoperability and support-process dependence	Valuable for support and recovery, but vulnerable to connectivity and escalation gaps
Parts ID/Trace Capture	Moderate fit and lower documentation-sequence pressure	More feasible for pilot use, provided cross-system consistency is maintained

Safety, Adaptation, and Regulatory-Traceability Fit

Safety findings showed that the main wearable-related risks were not primarily device failures but disruptions to controlled task execution, record completion, and sign-off continuity. The most visible issues included missed or delayed sign-offs, incomplete documentation, procedural deviations, incorrect entries, and QA-linked nonconformances. These patterns indicate that wearable-enabled maintenance can introduce safety exposure when digital workflow interruptions affect authorization, documentation accuracy, or audit-ready evidence. The analysis distinguished between safe adaptations and risky workarounds. Safe adaptations were actions that allowed work to continue while preserving procedural control, documentation integrity, and traceability. Examples included escalating connectivity or synchronization issues to supervisors or IT support, using approved continuity procedures, correcting incomplete entries before closure, and preserving sign-off accountability despite temporary system interruptions. These adaptations supported operational resilience by helping maintain safe task progression without weakening compliance controls.

By contrast, risky workarounds were actions that bypassed or weakened required controls. These included delayed documentation, skipped digital steps, incomplete or retrospective sign-offs, fragmented evidence chains, and use of records that could not be clearly linked to the current procedure version. Such workarounds increased safety and compliance risk because they reduced auditability, weakened accountability, and created uncertainty about whether the task was completed under the correct procedural requirements. As summarized in Table 4, safety and regulatory-traceability patterns were closely connected. Traceability was strongest when wearable-supported workflows preserved current procedure linkage, complete sign-off chains, retrievable audit evidence, and cross-system record continuity. It weakened when interruptions or workarounds produced revision mismatch, fragmented audit retrieval, incomplete synchronization, or broken authorization links. This shows that safety and traceability should not be treated as separate concerns in wearable-enabled MRO; both depend on whether technical integration, process discipline, and documentation governance remain stable under operational pressure.

Overall, the findings suggest that wearable-related safety should be assessed through both deviation patterns and recovery capacity. Documentation and sign-off errors reflect system vulnerabilities, while safe adaptations reveal whether the organization can absorb disruptions without compromising control. This interpretation is consistent with aviation maintenance safety literature showing that documentation and certification errors often emerge from interactions among workflow, supervision, and organizational conditions rather than isolated technician mistakes (Abbas & Khare, 2024; Clare & Kourousis, 2021). It also supports Safety-II and HFACS-informed analysis by showing that wearable deployment should be evaluated not only by error reduction but also by the ability to

preserve traceability and recover safely during operational variability (Illankoon et al., 2019; Lima Brugnara et al., 2023).

Table 4. *Safety and Regulatory-Traceability Patterns in Wearable-Supported Workflows*

Domain	Main Observed Pattern	Discussion/Implication
Documentation and Sign-Off Deviations	Missed sign-offs, delayed entries, incomplete records, QA nonconformances	Safety exposure was concentrated in record integrity and authorization continuity, rather than device faults alone
Preconditions and Workflow Friction	Connectivity instability, downtime, interruption burden, fragmented task flow	Feasibility constraints increased the likelihood of deviations and workaround dependence
Adaptive Recoveries	Escalation-based recovery, continuity actions, supervisor/IT support	Safe adaptation was possible when organizational support structures were present
Risky Workarounds	Bypassed digital steps, delayed recording, fragmented evidence chains	Adaptation became unsafe when it weakened procedural control or traceability
Traceability Strengths	Correct revision linkage, intact sign-off chain, retrievable evidence continuity	Compliance compatibility depended on preserving auditable documentation across systems
Traceability Gaps	Version mismatch, fragmented retrieval, record inconsistency, broken authorization links	Traceability breakdowns reflected upstream technical, procedural, and governance weaknesses
Traceability Gaps	Version mismatch, fragmented retrieval, record inconsistency, broken authorization links	Traceability breakdowns reflected upstream technical, procedural, and governance weaknesses

Integrated Deployment Implications and Readiness Profile

Taken together, the findings indicate a clear cross-layer mechanism linking implementation conditions, operational performance, safety, and traceability. Weak workflow fit, infrastructure reliability, interoperability, and implementation process discipline reduced feasibility and fidelity, increased reliance on workarounds, and ultimately weakened audit-ready traceability. In contrast, stronger governance, clear escalation pathways, training support, and recoverable workflow structures improved controlled execution, supported safer adaptation, and preserved evidence continuity. This pattern reinforces the study's central argument that wearable operationalization in MRO is best understood as an implementation-safety-traceability challenge rather than a simple device-adoption problem.

The resulting readiness profile was moderate rather than fully deployment-ready. The strongest readiness was observed in e-task/procedure execution and inspection/sign-off, while troubleshooting/remote assist remained the weakest area, and parts ID/trace capture occupied an intermediate position. Across the case, documentation governance and regulatory-traceability readiness were relatively stronger than infrastructure reliability and technical integration, indicating that the main barriers to wider implementation were not conceptual acceptance or strategic intent, but operational robustness and system continuity. As shown in Table 5, these patterns support a phased deployment logic in which stronger workflow areas may proceed to targeted pilot expansion, whereas weaker areas require remediation-first implementation.

These cross-layer findings align with implementation science literature showing that intervention success depends on the interaction of contextual determinants, process quality, and outcome performance rather than on adoption alone (Proctor et al., 2023; Reardon et al., 2025). They also extend readiness and maturity studies by showing that, in regulated aircraft maintenance, moderate readiness may still justify phased expansion when governance and traceability controls are relatively strong, even when infrastructure reliability and technical integration remain limiting conditions (Flamini & Naldi, 2022; Abdullah & Al-Ahmari, 2025).

Table 5. *WMRI Summary and Deployment Recommendations by Workflow Unit*

Workflow Unit	WMRI Composite	Readiness Band	Deployment Implication
Facility Overall	0.62	Moderate	Conditional expansion
E-Task/Procedure Execution	0.65	Moderate	Targeted pilot expansion
Inspection/Sign-Off	0.65	Moderate	Targeted pilot expansion
Parts ID/Trace Capture	0.60	Moderate	Pilot with safeguards
Troubleshooting / Remote Assist	0.57	Moderate	Pilot only/remediate first

Implications, Contributions, and Limits

This study makes three specific contributions. First, it reframes the deployment of smart wearables in aircraft maintenance as an implementation-safety-traceability problem, rather than a simple technology-adoption issue. Unlike studies that focus mainly on device usefulness or digitalization benefits, this study shows that wearable value depends on workflow fit, infrastructure reliability, process discipline, and audit-ready documentation.

Second, the study contributes a record-based method for assessing implementation outcomes in regulated MRO settings. Instead of relying solely on user perceptions, it demonstrates how feasibility, fidelity, penetration, sustainability, and cost burden can be examined through auditable records, such as system logs, QA reports, controlled procedures, support records, and traceability evidence. This addresses the gap in operational guidance for evaluating wearable-supported workflows using verifiable documentary evidence.

Third, the study introduces the WSIT-MRO framework and WMRI as practical tools for linking implementation readiness, safety behavior, and regulatory-traceability fit. This provides a structured way to identify whether wearable-supported workflows are ready for expansion, require safeguards, or need remediation before scale-up. The main novelty is the integration of implementation science, Safety-II/HFACS-informed analysis, and audit-grade traceability into one decision-support approach for regulated aircraft maintenance.

For MRO operators, the findings suggest that smart wearables should be implemented through a phased and readiness-based approach. Before expansion, operators should verify: stable connectivity and synchronization, current procedure linkage, complete sign-off accountability, retrievable audit evidence, workflow compatibility, training readiness, and escalation procedures for system interruptions. Workflows with stronger readiness, such as e-task execution and inspection/sign-off, may proceed to controlled pilot expansion. Workflows with weaker readiness, such as troubleshooting or remote assistance, should undergo remediation first. For regulators and quality assurance units, wearable integration should be treated as a documentation-control and compliance-assurance issue, not merely as a digital tool upgrade. Review should focus on whether wearable-supported records remain linked to approved procedures, authorized users, valid timestamps, corrective-action evidence, and retrievable audit trails. Deployment should be limited or deferred when there is a revision mismatch, broken sign-off continuity, fragmented evidence, or unresolved traceability gaps.

These findings should be interpreted within the study's limits. The retrospective, document-based design provides strong evidence on governance, traceability, and operational process conditions. However, it does not capture technician perceptions, informal work practices, or real-time human factors behavior. The findings are also bound to the Philippine MRO context and are intended for analytical transferability rather than statistical generalization. Future studies should validate the WSIT-MRO framework and WMRI across multiple MRO sites, combine documentary evidence with interviews or observations, and test the model in prospective wearable pilot implementations.

Conclusion

This study concludes that smart wearable deployment in aircraft maintenance should be treated not merely as a digital tool adoption issue, but as a controlled implementation challenge involving safety, documentation governance, and regulatory traceability. The findings show that wearable value depends on whether the technology preserves workflow discipline, sign-off accountability, revision control, and audit-ready evidence continuity while supporting efficient maintenance execution. The study makes three main contributions. First, it offers the WSIT-MRO framework as an integrated lens for evaluating wearable deployment through implementation readiness, safety behavior, and regulatory-traceability fit. Second, it highlights audit-grade traceability as a core condition of successful wearable implementation, showing that evidence continuity, authorization linkage, and retrievable documentation are not secondary compliance concerns but central deployment requirements. Third, it demonstrates that implementation outcomes such as feasibility, fidelity, penetration, and sustainability can be assessed through documentary and archival evidence, providing a practical alternative when direct human-participant data are not used.

For practice, the findings support phased, readiness-based deployment rather than immediate enterprise-wide rollout. MRO operators should prioritize workflows with a stable procedural fit, support routines, connectivity, sign-off controls, and traceability safeguards, while addressing weaker areas before scale-up. Regulators and quality assurance units should evaluate wearable integration as a documentation-control and compliance-

assurance issue, particularly where revision mismatch, fragmented audit retrieval, or broken authorization links may occur. Future studies should validate the WSIT-MRO framework and WMRI across multiple MRO facilities and aviation regulatory contexts. Further research should also combine documentary evidence with human factors data, such as interviews, observations, or usability assessments, to capture technician experience, informal adaptations, and real-time workflow behavior during wearable-supported maintenance.

Contributions of Authors

Arthur Dela Peña, as the corresponding author, led the study conceptualization, framework development, methodology design, data interpretation, and manuscript writing and revision. Jefferson Clariza contributed to literature support, data interpretation, validation of analytical outputs, and manuscript review. Mary Ann Aballiar-Vista contributed to methodological refinement, document review, interpretation support, and manuscript editing. All authors read and approved the final version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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