MANHATTAN UNIVERSITY

Mechanical Engineering Department

Manhattan University

A.E.R.I.S. | Aircraft Enhanced Resilience & Intelligence System

2026 Gateways to Blue Skies:
RepAir | Advancing Aircraft Maintenance

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A.E.R.I.S.

Aircraft Enhanced Resilience & Intelligence System

GATEWAYS TO BLUESKIES

Project Summary:

Aviation Maintenance Area:

Unscheduled Maintenance & Predictive Maintenance

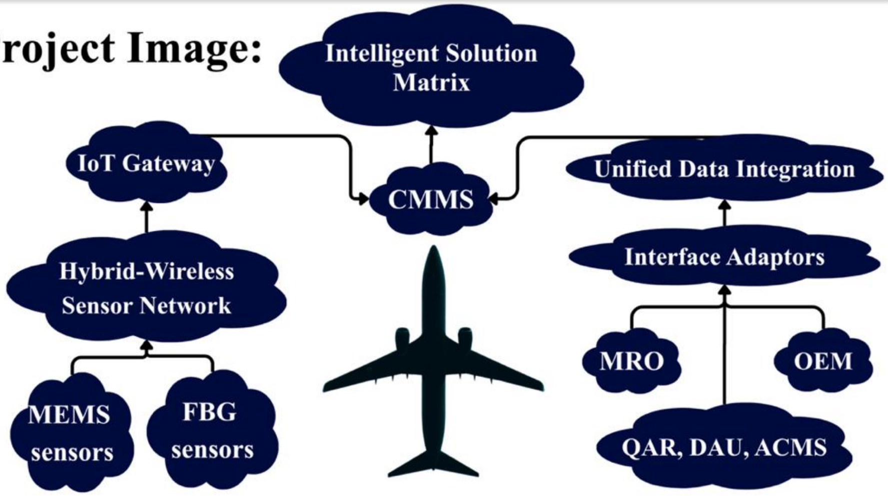
Use Case:

Improving the predictive maintenance technologies and unscheduled maintenance of aging aircraft fleet.

Overview:

A.E.R.I.S. bridges the predictive maintenance gap in legacy commercial aircraft through retrofittable sensor networks and unified data integration increasing their life and maintenance efficiency.

Project Image:



Team Composition:

Manahill Gohar – Mechanical Engineering, Senior

Labiba Siddika – Mechanical Engineering, Junior

Angie Centeno – Mechanical Engineering, Junior

Stacy Cabral – Mechanical Engineering, Junior

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Proposed Deployment Timeline:

Phase 1: Architecture design and feasibility (2026-2028)

H-WSN and IoT gateway architecture established and data integration programs developed. Sensors modified with self-harvesting features prototyped in lab.

Phase 2: STC application and initial testing (2028-2030)

STC application for H-WSN and design certification started. Interface adaptors and gateway modules installed. Sensors ground tested.

Phase 3: STC completion and flight testing (2030-2031)

The full software, data integration, and sensor network performance flight tested and final STC approved.

Phase 4: Fleet-wide implementation (2031-2035)

A.E.R.I.S. is fully installed and deployed to A320ceo fleet and providing expected performance.

Abstract

Aircraft Enhanced Resilience Intelligence System (A.E.R.I.S) is a two-part predictive system designed to help increase the flight span of ageing aircraft and reduce Aircraft on Ground (AOG) time. Professionals were consulted to get a better understanding of how changes to the aircraft will work. Some of the changes made included creating an adapted timeline and cost analysis for the first aircraft, providing an environmental analysis, and adjusting the phasing of the system.

To provide accurate data, we shifted focus to solely Airbus A320ceo as our primary test aircraft and base for testing and developing the system with an average size of 103 planes per fleet. The timeline was updated with feedback provided by Aircastle representatives, Howard Brewer and Ximena Sloane. Based on the feedback provided, the Supplemental Type Certificate (STC) development and application have been split into a two-part parallel development. Phase 1 now includes the participation of Directive Engineering Representatives (DER's) in the later stage of this phase to facilitate the process of meeting the Federal Aviation Administration (FAA) requirements. Phase 2 consists of submitting an STC application, and the full on-board retrofit on only one aircraft will occur later in this stage, instead of a limited retrofit installation. Phase 3 has been altered to focus on flight testing, certification completion, and operational validation for both on-board and ground-based systems for the next year on only one aircraft. In the later stage of this phase, the needed paperwork and compliancy checks for FAA approval would commence to allow the expansion to the entire fleet, 103 Airbus A320ceo. A cost breakdown has been added of the rough overall estimate costs to develop the first STC by using industry benchmark prices. A hypothetical total cost for full fleet implementation was obtained from Gary Weissel, an expert in aircraft interiors. Return on Investment (ROI) percentages were obtained for both low-end and high-end cost estimates and compared to industry researched ROI ranges for a well-implemented predictive maintenance system.

The aviation industry does not lack data; it lacks a practical way to connect that data across legacy systems and turn it into coordinated action. By 2035, aging aircraft will still be flying. The challenge is not replacing them but enabling them to operate with the same predictive awareness as modern fleets, without requiring full redesigns or unrealistic retrofit costs. Due to the late detection of failures and misalignments in legacy aircraft, their operational lifespan is reduced to well below their maximum potential. When a legacy aircraft must be replaced, companies such as Airbus losing over \$98M to \$308.1M [1]. Our system is designed to allow the legacy fleets to fly closer to their maximum potential, saving resources, reducing environmental impacts, improving detection, and allowing companies to save millions of dollars.

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1. Situational Assessment

1.1. Economic Impact (AOG)

When unexpected component failures occur, AOG events create cascading operational disruption. Industry professionals interviewed for this proposal consistently identified unplanned AOG events as one of the most financially and operationally damaging outcomes of reactive maintenance. Costs include lost revenue, passenger accommodation, crew rescheduling, maintenance labor, and expedited logistics for replacement parts [2]. Without early detection and coordinated parts positioning, operators are forced into urgent, high-cost response cycles.

1.2. Retrofitting Constraint

Condition-based maintenance has demonstrated measurable cost and efficiency benefits in modern aircraft. However, extending these capabilities to aging fleets presents a structural challenge. Traditional wired sensor retrofits require additional cabling, adding weight and cutting into fuel efficiency, integration into legacy avionics architectures, and extensive certification, often making large-scale modernization economically prohibitive for older airframes [3]. As a result, many legacy aircraft remain excluded from the predictive maintenance frameworks increasingly becoming the standard in newer platforms. This creates a widening capability gap between digitally integrated fleets and aging aircraft that must continue operating safely and economically through 2035 and beyond.

1.3. Data Fragmentation

Even when legacy aircraft generate relevant operational data, through Quick Access Recorders (QAR), Data Acquisition Units (DAU), or maintenance logs, this information is frequently siloed across disconnected systems. Maintenance data is typically divided among: Original Equipment Manufacturer (OEM)-controlled design and performance models, operator-collected flight telemetry, and Maintenance, Repair, and Overhaul (MRO)-maintained “as-found” and “as-maintained” records. These datasets rarely operate within a unified analytical environment. Differences in data formats, communication protocols, and proprietary access restrictions prevent critical maintenance data that exists in separate silos from being combined into a single, actionable view of aircraft health.

Technician interviews conducted for this proposal revealed that this fragmentation contributes to delayed diagnostics, repeated “No Fault Found” troubleshooting cycles, inefficient parts positioning, and heavy documentation burdens during shift handovers. In many cases, failures are addressed reactively not because data is unavailable, but because it cannot be translated into coordinated operational insight.

1.4. Human Consequences

When aircraft data cannot be seen as one connected system, maintenance becomes reactive by default. Intermittent faults that only appear in flight often cannot be reproduced on the ground, leading technicians to replace components as a precaution rather than with certainty. Parts are then ordered urgently because early signs of degradation were never recognized or acted on. Meanwhile, maintenance teams working around the clock must complete documentation and shift handovers using incomplete or disconnected information.

2. Use Case and Proposed Solution

2.1. Target Use Case

This proposal focuses on unscheduled maintenance events in legacy narrow-body aircraft, particularly aging Airbus A320ceo platforms that remain heavily utilized in cargo and secondary markets. These aircraft rely primarily on reactive fault detection and time-based overhaul schedules, causing high-wear subsystem failures to frequently trigger unplanned AOG events.

A.E.R.I.S targets four subsystems where unexpected failures disproportionately drive time and cost. For example, landing gear and wheel/brake assemblies experience extreme vibration and thermal loads during takeoff and landing. Current maintenance practices rely on scheduled overhauls and post-flight inspections, which often miss gradual degradation that leads to bearing failures, brake fade, or hydraulic leaks. Wing and fuselage primary structure is susceptible to fatigue accumulation, particularly at known high-stress regions such as lap joints, spars, and repaired composite areas [4]. Aging aircraft are vulnerable to Widespread Fatigue Damage (WFD), where multiple cracks develop simultaneously and are often not detected until they reach critical size [5]. Which then causes a longer grounding period for repairs. High-lift systems (flap tracks and slats) are complex mechanical assemblies prone to wear, misalignment, and binding. Failures are typically identified late through manual rigging checks rather than continuous monitoring. Environmental Control System (ECS) packs and Auxiliary Power Units (APU's) contain rotating machinery where vibration imbalance and thermal creep can develop gradually. Legacy aircraft monitors only basic temperature thresholds, often missing early degradation patterns that precede shutdown events.

Across these subsystems, relevant data does exist within onboard systems such as the QAR, DAU, Health and Usage Monitoring System (HUMS), and Aircraft Condition Monitoring Systems (ACMS) in the form of Electronic Centralized Aircraft Monitoring (ECAM), but it remains fragmented, formatted in incompatible legacy protocols, and inaccessible to modern predictive analytics frameworks. The challenge is not inventing new sensor physics, instead it's connecting proven sensing technologies into a deployable architecture that legacy fleets can realistically adopt by 2035.

2.2. Proposed System

We propose **A.E.R.I.S**: a Hybrid Wireless Sensor Network (H-WSN) implementation in areas of high risk on older fleets and a modular retrofit architecture designed to extend predictive maintenance capability for aging fleets with minimal invasive structural modification [6]. This system will take current ideas that are in use through different companies and combine them into one main programming system. This system consists of two integrated layers: (1) Hybrid Wireless Sensor Network (H-WSN) installation and Data Integration, and (2) an Intelligent Solution Matrix (ISM). The first part of the system requires retrofitting. Placing different wireless sensors and Internet of Things (IoT) components into certain parts of the plane will allow us to keep track of any changes before, during, or after the flight. Throughout the time, all data collected by the sensors will be transferred to an intelligent solution matrix (layer 2).

2.2.1 Layer 1: Sensor Network Integration and Data Integration

Layer one addresses two core barriers to predictive maintenance on legacy narrow-body aircraft: adding standardized condition monitoring to subsystems that lack continuous health coverage such as landing gear, wings, high-lift systems, and Environmental Control System (ECS) / Auxiliary Power Unit (APU) components and unifying fragmented data from existing onboard systems into a predictive-ready format.

A.E.R.I.S. deploys a H-WSN, a distributed autonomous sensors management system that monitors physical and environmental conditions and passes the data through a wireless communication network gateway, to support existing, proposed, and future sensing technologies with different power and integration requirements [7][8].

Micro-electromechanical systems (MEMS) vibration and temperature nodes are low-power devices that are to be self-powered through piezoelectric (PZT) vibration energy harvesting [9]. Each node pairs a PZT patch tuned to its target subsystem's characteristic frequencies with a supercapacitor bank that stores harvested energy and discharges it during low-vibration periods [10]. These nodes transmit wirelessly via low-power protocols like Zigbee or Bluetooth Low Energy (BLE) to local router nodes or directly to IoT gateway [11] [12]. Each MEMS node contains a sensing element (MEMS accelerometer and temperature sensor chip), a microcontroller for local edge processing, a short-range wireless radio, and the integrated PZT harvesting and supercapacitor power system. No batteries and no structural wiring are required.

Fiber Bragg Grating (FBG) strain sensors require an interrogator unit to process the reflected wavelength data they generate [13]. To power the interrogator, a hybrid approach with PZT vibration harvesting provides baseline power during flight operations when structural vibration is present, supplemented by a supercapacitor bank that charges during high-vibration phases and sustains the interrogator during low-vibration cruise. FBG sensors bonded to structural zones are connected via lightweight optical fiber runs to a compact, aerospace-grade miniaturized FBG interrogator unit (such as the AGTR-NEO, which provides fast parallel sampling, high-resolution sensing, and onboard processing in a reduced size, weight, and power form factor with standard Ethernet output) [14]. The interrogator outputs digitized strain data electronically to the IoT gateway's data concentrator. Optical Time Domain Reflectometry (OTDR) Interrogation method is used for its advantages on large networks and longdistance sensing benefits [15]. Because a single interrogator can monitor dozens to hundreds of FBG sensors over one thin fiber cable, this semi-wired approach adds much less wiring, weight, and complexity than a traditional electronic strain gauge array, which requires a separate wire pair for every sensor.

Each sensor node in the H-WSN conforms to the A.E.R.I.S. node interface standard, which defines data format, transmission protocol, and metadata requirements. This open architecture design means new sensing updates that emerge before the 2035 deployment window can be incorporated during heavy scheduled maintenance checks without modifying the gateway or ground analytics infrastructure. Existing sensors already present on legacy aircraft and connected to the Central Maintenance Computer (CMC) are accessible to the H-WSN through a passive ARINC 429 bus tap.

As part of the H-WSN, select subsystems that are high maintenance are to receive a tailored sensor pairing for this proposal [16]. Landing gear and brake assemblies are fitted with wireless MEMs vibration and temperature nodes mounted on struts and brake housings to detect bearing wear and thermal fade trends before failure [17]. Wing and fuselage structural zones incorporate FBG strain sensors bonded to spars and skin panels [18]. These fiber-optic arrays track distributed load histories and detect localized overloads associated with fatigue progression. High-lift systems receive MEMS vibration-temperatures nodes on flap tracks and slat drive units to identify wear and misalignment signatures during deployment cycles. ECS packs and APU mounts incorporate MEMS nodes on housing and rotating assemblies to detect imbalance, degradation, or thermal creep in early stages [19] [20].

The IoT gateway is composed of data concentrators, edge computing units, and secure communication modules. Data concentrators aggregate both new wireless inputs and legacy onboard system outputs [21]. Edge computing units perform anomaly detection and compress telemetry before transmission, enabling real-time alerts while minimizing bandwidth [22]. Secure gateway modules transmit encrypted data to ground-based maintenance systems while remaining non-flight-critical to simplify certification under Supplemental Type Certificate (STC) pathways [23].

To integrate fragmented maintenance data across OEM, operator, and MRO databases, we implement Time Sensitive Networking (TSN) interface adapters that translate legacy protocols (ARINC 429, RS-232, CAN bus) into modern cloud-compatible formats [24]. Data mapping pipelines standardize terminology and units across fleets [25], while mirrored analytics environments allow machine learning model training without risking operational Computer Maintenance Management System (CMMS) databases [26]. This layer transforms “digitally dark” aircraft into connected platforms without redesigning the airframe. With this system, prediction failure technologies throughout the aircraft can be supported, and generationally divided data will be wirelessly transmitted into a logistics infrastructure.

2.2.2. Layer 2: Intelligent Solution Matrix

When the system detects a maintenance issue through the data collected in the first layer, the information is then passed to the decision layer (layer 2) for evaluation. Each determining variable: vibration, Temperature, Strain, Diagnosis, Confidence, Time Constraint, Part Availability, and Cost is assigned a numerical value on a scale from 1 to 5, where 1 represents the least favorable condition, and 5 represents the most favorable condition for a given solution. The system evaluates all available solutions by calculating a weighted score based on them. However, in certain situations, the weight of certain variables can be increased or decreased as they could make the situation worse.

The solution with the highest overall score is presented as the recommended course of action for the identified issue with a second proposed action following in the case that the first recommendation is not plausible. There are currently four paths that the system can recommend: In-house Fixing, Pre-Order Replacement Parts, Additive Manufacturing, and Heavier Monitoring. For example, when the issue has a moderate impact on aircraft performance or safety, the diagnosis of confidence is high, and parts are easily attainable or available. In-house fixing would be the best solution based on the given points.

A scenario for how the system works is this: if fuel pump bearing wear is detected with high confidence and the predicted remaining useful life is shorter than the part’s delivery lead time, the system recommends immediate procurement and scheduled installation during the next maintenance window. If OEM supply is constrained and regulatory approval pathways exist, additive manufacturing may be evaluated as a secondary option, not as the default strategy, but as a resilience tool. Figure 1 shows what will be shown once all data is placed, and solutions are provided. Safety override logic prevents low-confidence monitoring recommendations when criticality is high, ensuring that automated support augments, rather than replaces, qualified maintenance judgment.

When the recommended solution is shown, the next best solution will also be provided, along with reasoning as to why solutions were selected. Before moving on to the next layer, which implements the solution, the recommended solution must be reviewed and approved by a qualified engineer.

2.3. Operational Impact

The H-WSN integrates into existing workflows rather than replacing them. Technicians receive clearer diagnostics and reduced trial-and-error troubleshooting. Maintenance planners gain early warning to stage parts and labor before disruption occurs. Flight operations benefit from reduced unscheduled delays. Smaller operators gain access to predictive tools without building in-house analytics infrastructure. This architecture enables aging fleets to operate with predictive awareness comparable to modern aircraft, reducing unscheduled downtime while maintaining regulatory compliance and structural integrity.

3. Concept of Operations

3.2. System Overview and Data Flow:

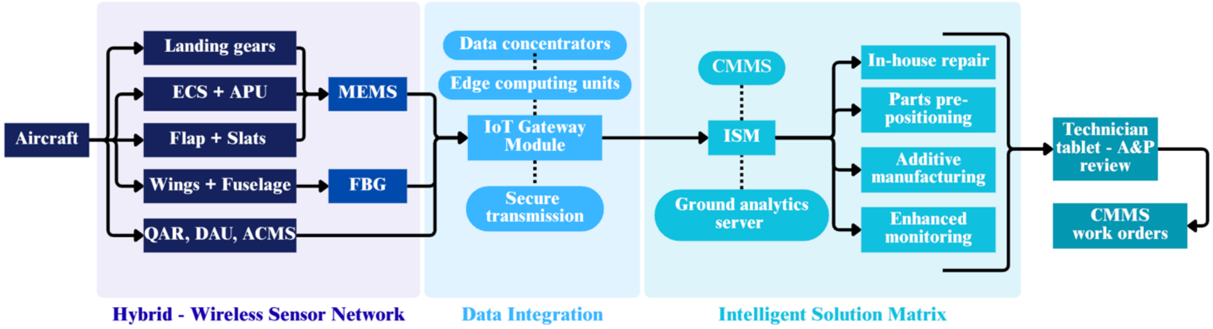


Figure 1: Concept of Operations

A.E.R.I.S. operates as a closed-loop predictive maintenance system across four phases: in-flight data collection, post-flight aggregation and transmission, ground analytics and decision support, and maintenance integration. Data flows from sensor nodes attached to high-risk subsystems, through an onboard IoT gateway, to ground-based analytics infrastructure, where the ISM converts condition data into ranked, technician-engineer-approved maintenance actions. At every stage, the system operates in parallel with existing certified avionics.

In-Flight Data Collection:

The two sensing subsystems of the H-WSN operate according to different power architectures and subsystem specific needs. Wireless MEMS nodes on landing gear struts and brake assemblies activate during takeoff and landing, when thermal and mechanical loads are at their peak. PZT vibration harvesting patches aligned to landing gear frequencies and supercapacitor storage sustaining operations. High lift system nodes activate during every flap and slat deployment cycle, while logging vibration signatures. ECS pack and APU mount MEMS nodes run continuously to track rotating vibration and thermal drift adding progressive degradation trend capture capability. The FBG strain sensors are bonded to wing spars and fuselage lap joints to record load histories continuously, cumulative strain accumulation, and anomalous patterns at fatigue-susceptible structural zones. Each FBG sensor is also paired with a reference sensor for true strain data. The compact on-board FBG interrogator, with hybrid-power unit, processes reflected wavelength data from all bonded sensors and outputs digitized strain readings. Each MEMS node processes data locally at the microcontroller level before wireless transmission. When a real-time reading exceeds the baseline threshold, the node timestamps the event, logs contextual flight parameters including phase of flight and gross weight, and queues the anomaly alert for transmission rather than streaming raw data continuously. This edge-processing architecture minimizes wireless bandwidth and conserves energy by transmitting only datasets already anomaly-tagged and prioritized before reaching the gateway.

One important design principle here is baseline discrimination. For example, structural vibration during turbulence can produce transient accelerometer readings that resemble bearing wear signatures. The system addresses this by correlating sensor output against flight data recorder inputs so when turbulence is logged by the existing flight management system, that time window is flagged and the anomaly detection threshold is temporarily adjusted. This prevents false positives from environmental noise without requiring continuous human oversight.

Post-Flight Data Aggregation and Transmission:

Upon gate arrival, the aircraft's IoT gateway automatically connects to available Wi-Fi or cellular infrastructure. The IoT gateway collects queued sensor data and extracts parameters from legacy systems (QAR, DAU, ACMS, CMMS), translates them into standardized format, then transmits them to ground servers. For remote locations, the gateway stores data locally until connectivity is available.

Ground Analytics and Decision Support:

Ground-based analytics servers receive aggregated datasets and begins two parallel processing streams. The first is anomaly classification, where machine learning models trained on fleet-wide historical QAR, ACMS, and MRO records on CMMS analyze vibration frequency spectra, temperature drift curves, and cumulative strain histories to identify degradation signatures and match them against known failure mode libraries. Each classification carries a quantified confidence level.

The second stream is fleet correlation. When an anomaly is detected on one aircraft, the system queries fleet-wide data to determine whether similar patterns appear across other airframes of the same type and age. This fleet-level intelligence allows A.E.R.I.S. to distinguish between a localized component issue and an emerging fleet-wide degradation pattern.

Once the anomaly is classified with confidence, the ISM evaluates it against eight weighted variables: Problem Severity (18%), Vibration (15%), Temperature (15%), Strain (15%), Part Availability (13%), Diagnosis Confidence (12%), Time Constraint (7%), and Cost (5%). Each variable is scored on a 1-5 scale, and the weighted variables maps to one of four output paths: In-House Repair, Parts Pre-Positioning, Additive Manufacturing, or Enhanced Monitoring. Safety override logic prevents Enhanced Monitoring from being recommended when component criticality is high regardless of its score.

Maintenance Integration and Stakeholder Roles

The ISM's ranked recommendation, including the top-scoring action, the next-best alternative, supporting sensor data, trend plots, and confidence level, is shared to the lead A&P mechanic through a dedicated technician tablet connected to the ground analytics server. The A&P reviews the ISM alongside their own physical observation of the aircraft and existing CMC fault data. No action proceeds without this human review and sign-off. For findings involving structural subsystems, fleet-wide anomaly patterns, or recommendations that would alter a scheduled maintenance interval, the A&P escalates to the airline's reliability engineering team. This ground-based analytical role reviews the ISM's fleet correlation data and confidence history before authorizing any maintenance program change. This escalation path is also triggered automatically by the ISM depending on anomaly type and confidence thresholds.

Upon A&P approval, outputs flow through two parallel channels. First, a structured work order, pre-populated with part numbers, labor hour estimates, required tooling, and applicable task card references, is entered into the operator's CMMS. This work order appears in the CMMS in the same format as any other manually generated work order, maintaining continuity with existing compliance tracking, scheduling workflows. The CMMS also receives the ISM's parts pre-positioning requests, automatically triggering procurement actions through existing MRO supply chain connections. Second, the approved task guidance remains visible on the technician tablet throughout execution, providing the A&P with real-time reference to diagnostic evidence and ISM reasoning during the repair.

Upon completion, the A&P signs off the work in the CMMS, closing the work order and generating the required return-to-service documentation. The CMC continues to display its own certified fault history on the Multifunction Control and Display Unit (MCDU) as it always has. A.E.R.I.S. does not alter, supplement, or compete with the CMC's display. The two systems operate independently and in parallel. This operational model enhances existing workflows while providing data-driven decision support that reduces unexpected AOG time and extends operational functionality of aging aircraft.

3.3. Interoperability with Existing Processes and Technologies

Interoperability is achieved through a layered integration approach that enhances data accessibility and the capabilities of analytics while preserving certified avionics [20]. The system converts legacy data into model-based formats and aligns it with existing codes used by current CMMS platforms ensuring continuity of work orders, technician interfaces, audit trails, regulatory documentation, and scheduled inspections, while preserving critical elements such as MEL protocols, deferred defect tracking, QAR/FDR (Flight Data Recorder) data, Onboard Maintenance System (OMS), and Engine Health Monitoring System (EHMS). Rather than replacing these systems, they would operate in parallel, which supports the inclusion of older fleets while aligning with the industry progression of Digital Twins and advanced predictive/preventive maintenance system. Operating alongside existing processes, failure trends and health-monitoring data are integrated into structured maintenance methodologies such as Maintenance Steering Group-3 (MSG-3), supporting FAA compliance while improving data-driven maintenance planning. Data concentrators, edge computing units, and gateway modules enable secure data transfer from aircraft systems to ground-based analytics platforms without replacing existing onboard recorders. The integration of wireless, self-harvesting sensor network enables further expansion of data collection with minimal added wiring, weight, or maintenance burden.

4. Path to Deployment

4.2. Deployment Timeline

The proposed retrofit solution consists of an on-board H-WSN and development of a ground-based ISM and data integration system. A parallel development approach will be taken in which the on-board H-WSN and IoT gateway, consisting of interface adaptors, self-energy harvesting sensors, data concentrators, gateway modules, and edge computing units, is developed under certification constraints from the FAA requirements for an STC. While ground-based systems are developed in parallel with the on-board components without direct STC certification requirements.

Phase 1, spanning approximately one to two years, focuses on architecture definition and feasibility. During this phase, the H-WSN and IoT gateway architecture is established, and applicable certification considerations are identified. Laboratory testing is conducted to advance the self-energy harvesting sensor technology from Technology Readiness Level (TRL) four to six, with emphasis on power stability, signal reliability, and environmental durability. Legacy avionics interfaces, including ARINC-based systems, health monitoring units, and quick access recorders, are analyzed, and Interface Control Documents are developed to define data translation into standardized formats compatible with CMMS. In parallel, ground-based components are developed, including a structured data mapping framework to standardize and validate incoming data, a data mirroring architecture to enable aircraft-to-ground data transfer, and the conceptual design of the ISM, including model selection and integration with maintenance workflows. Designated Engineering Representatives (DERs) will be engaged during the later portion of this phase to guide certification strategy and ensure alignment with FAA regulatory requirements.

Phase 2, with an estimated duration of approximately two years, encompasses system development, integration, and FAA certification activities for the H-WSN. This includes submission of the STC application and iterative refinement of system design based on regulatory feedback. Installations of hardware components such as the interface adaptors as non-intrusive ARINC bus readers to enable data acquisition without affecting aircraft system integrity would occur. Self-energy harvesting sensors are deployed and validated through ground and simulated flight testing as needed, advancing TRL to six through seven, while environmental qualification, electromagnetic compatibility, and system safety assessments are performed. Simultaneously, ground-based development progresses with validation of data mapping accuracy, implementation of data mirroring pipelines, and training of ISM predictive models using real and simulated data.

Phase 3 focuses on flight testing, certification completion, and operational validation for the next one year. Formal flight test programs are conducted to demonstrate system reliability, data integrity, and non-interference with aircraft systems, with approximately five hundred to one thousand flight hours accumulated per aircraft type to support certification. This phase advances system maturity to TRL seven through eight and enables final STC approval. End-to-end integration between on-board data acquisition and ground-based systems is verified, ensuring consistency and synchronization across all platforms. The ISM transitions into a fully operational decision-support system functioning alongside maintenance scheduling processes, while preparations for fleet expansion, including compatibility assessments for additional aircraft types, are initiated in coordination with the FAA.

Phase 4, would occur over the span of four years targeted for completion by 2035, involves full-scale deployment across the legacy fleet containing an average of 130 Airbus 320ceo's [27]. Installation of the certified H-WSN and IoT gateway is conducted during scheduled heavy C maintenance intervals occurring every 18-24 months by MRO providers. At this stage, the system achieves TRL eight through nine and full operational integration, with ground-based components including data mapping, data mirroring, and the ISM fully mature and embedded within maintenance workflows. The completed system enables predictive maintenance capabilities, reduces AOG events, and delivers measurable improvements in operational efficiency and asset utilization.

4.3. Policy and Regulations

The system will be implemented using a phased certification strategy aligned with STC requirements established by the FAA. Throughout the deployment process, the STC framework will require verification, validation, and adherence to applicable regulatory standards for all onboard technologies. Hardware components within the wireless sensor network will be qualified in accordance with DO-160G to demonstrate environmental survivability under conditions such as temperature variation, vibration, humidity, and altitude cycling [28], and will comply with DO-307A requirements to ensure electromagnetic compatibility with existing aircraft systems[29].

Software components associated with onboard processing, particularly within edge computing units, will be developed and verified in accordance with DO-178C [30], with consideration of earlier guidance from DO-178B [31] where applicable. Energy-harvesting sensor prototypes will undergo laboratory validation to replicate operational vibration environments and confirm that power generation capabilities meet sensor performance requirements prior to integration. Interface adaptors will be developed in accordance with applicable FAA guidance for avionics interfaces and data acquisition systems, ensuring compatibility with existing aircraft data buses without impacting system integrity [32].

Ground-based components, including data mapping, data mirroring, and predictive analytics systems, are not subject to direct STC certification requirements; however, they will be developed in alignment with relevant data governance and aviation guidance to ensure secure, reliable, and traceable data handling [33]. Collectively, this structured certification approach ensures that all onboard systems meet required safety and performance standards while enabling the concurrent development of advanced data-driven maintenance capabilities.

4.4. Technology Readiness Level

There are two categories of technologies introduced throughout this proposal: Software/data integration and hardware components. These include the WSN, data mapping, the ISM, MEMS vibration-temperature sensors, and the FBG strain sensors as assessed for their TRL on Table 2. Modern aircraft contain a WSN that is used to send real-time data to grounded systems for predictive data analytics, giving this component a TRL number of 5 or 6. Some wireless sensors are used in older aircraft but is not prioritized, therefore a prototype demonstration is required. Data mapping is being used in the avionic industry in the form of Geographic Information System (GIS) technology to manage aeronautical data. However, the rule-based sematic data mapping process required for this system will have to undergo testing and prototype approval, giving this component a TRL number of 5 or 6. The ISM will require research and a prototype, placing a TRL of 4 because predictive data analytic methods such as the one proposed exist already with the dominating one being the Airbus Skywise ecosystem except they're not applicable to older fleets [34]. For the hardware components, current MEMS sensors achieve a TRL 7-8 because of their commercial industrial CBM applications with NASA gateway prototypes illustrating aircraft integration paths [35]. Self-powering through integrated lead zirconate titanate (PZT) patches that are tuned to gear and flap frequencies with supercapacitors to store the power generated, is at TRL 4-5 since lab demos are produced [36]. Since both parts of the sensor exist successfully separately, prototyping this combined model is feasible by 2035, which justifies a TRL 4-5. FBG strain sensors reach TRL 7-8 because of the Boeing 777/787 structural testing and Delta's experimental retrofit on a Boeing 767-300ER, showing retrofit feasibility but not yet fleet wide standardization [37]. Similarly to the MEMS, the harvesting feature remains at TRL 4-5 with working lab prototypes. Therefore, FBG sensors also received a combined score of TRL 4-5 for the modification.

4.5. Training Plan

IT and cybersecurity personnel undergo coordinated training covering gateway configuration, data mirroring, cloud interface protocols, intrusion detection, access control policies, and secure data transmission. Reliability teams receive training on predictive model interpretation, regulatory compliance alignment, and data analytics literacy. Maintenance technicians complete training on dashboard navigation, alert interpretation, and IoT sensor measurement understanding. Annual refreshers maintain currency across all roles.

4.6. Cost Analysis

The total cost of implementing the proposed system can be categorized into three primary components: the development of an STC for the on-board components, equipment procurement costs for the on-board systems, and the development of the ground-based system and associated hardware. Among these, the STC development represents the dominant cost driver and is therefore the most accurate price. Due to the early stage of system definition and the variability in aircraft configurations, accurately scoping total STC development costs is challenging. As a result, a rough order of magnitude (ROM) estimate was developed based on expert consultation with an aircraft interiors expert.

This assessment indicates that the cost of developing the initial STC is expected to fall within a range of $5 million to $8 million. Given the magnitude of this cost and the uncertainty associated with early-stage estimates, other cost components, such as hardware procurement and installation, are considered economically secondary in impact at this stage and are not evaluated in comparable detail until further design maturity is achieved.

To better understand the composition of STC development costs, the total estimate was further decomposed into key cost elements (e.g., engineering, testing, certification, and documentation), along with their typical proportional contributions. This breakdown was informed through industry insight provided by a representative at Aircastle. The corresponding low-end and high-end estimates for each cost element are summarized in *Table 2* in the appendix.

A Return on Investment (ROI) percentage was evaluated for the hypothetical total investment costs of a full fleet expansion to compare to industry ROI percentages for well-implemented predictive maintenance programs. To conduct this, the economically secondary prices were taken into consideration for the purpose of obtaining an ROI for an average fleet size of 103 Airbus A320neo planes [38]. Hypothetical total cost breakdowns can be seen in *Table 3* in the appendix.

The positive cash flow is the recurring money expected to be saved annually from implementing this system. This will be the annual losses from AOG events for the fleet; which was obtained from existing information on AOG events and calculated as the product of money lost due to AOG events per hour, the average duration of one AOG event, and an average amount of annual AOG events per aircraft [39]. A crude factor of safety of 0.5 was applied to this savings cost under the assumption that at best A.E.R.I.E.S. is about 50% efficient at reducing AOG events or duration. The equipment procurement and installation costs for the on-board hardware would fall in the $100 thousand to $500 thousand range [40] but for the calculations the total cost for this was assumed to be $500 thousand for conservative results. The development and installation of the ISM and other ground-based component costs were obtained using the costs to develop a machine learning predictive maintenance analysis software as a baseline for comparison purposes. This non-recurring cost was taken to be $300 thousand for an enterprise grade platform [41].

The ROI percentages are tabulated in the appendix under *Table 4*. For the low-end total cost range, the ROI was calculated to be 185.61% and for the high-end total cost range the ROI was calculated to be 171.28%. Industry research shows an ROI of 200% to 500% for implemented systems like these [42]. While this provides strong economic potential, it is subject to several limitations that should be considered when interpreting the results. The projected savings are based on an assumed 50 percent reduction in AOG events, which may vary depending on system performance, sensor data quality, and operational adoption. Additionally, AOG cost estimates are derived from generalized industry averages and may not fully reflect variations across different aircraft types, route structures, and airline operations. The cost assumptions used in the analysis are intentionally conservative, including the use of upper-bound retrofit costs and fixed development estimates, but actual costs may differ due to supplier pricing, installation complexity, and economies of scale. Furthermore, the analysis focuses primarily on AOG-related savings and does not account for additional benefits such as reduced unscheduled maintenance, extended component life, improved fuel efficiency, or labor savings, which may result in an underestimation of total value. Potential risks associated with certification timelines, system integration, and deployment logistics may also impact both overall costs and the timing of realized savings. Finally, the effectiveness of the ISM is dependent on the availability of high-quality data and sufficient model training, meaning that performance, and therefore financial returns, may be lower during early stages of implementation before the system reaches full maturity.

The economic return from the implementation of similar predictive maintenance retrofits is outlined by major operators such as Delta Air Lines and Lufthansa. They have reported 15–25% reductions in maintenance and operational costs through the adoption of predictive maintenance and digital monitoring technologies [43]. At the industry level, these improvements correspond to $2–5 billion in annual savings, driven by reductions in unscheduled maintenance, improved component life management, and decreased aircraft downtime. For aging aircraft platforms that typically experience higher failure rates and maintenance burdens, incremental improvements in fault detection and maintenance scheduling yield large cost savings. As a result, despite higher retrofit complexity, the payback period is often short around 1 to 3 years [42], especially when deployed across medium to large fleets where fixed development costs can be distributed.

4.7. Risk Analysis: Technical and Cybersecurity

Major risks can be separated into two main categories: technical risks and cybersecurity risks. Technical risks include avionics interference, and sensor reliability. The avionics interference risk is the potential electromagnetic interference or the unintended interaction between certified avionics systems and the gateway modules. Sensor reliability is impacted by harsh environments that cause degradation. A specific technical risk involves “False positives”, where external environmental factors such as heavy wind turbulence could be incorrectly flagged as component failure. To mitigate them adhering to the FAA guidelines, maintaining early regulatory coordination, frequent testing and maintenance specifically for the sensors bringing down the residual risk, and advanced baseline calibration to reduce risk of false positives. Cybersecurity risks involve unauthorized data access and the possibility of a breach through the gateway modules or ground connectivity. To enhance protection implementing software checks and locks, which are mechanisms to ensure data integrity and safe concurrent access to resources. Additionally, utilizing data mirroring, which creates a secure real time identical replica of data across multiple servers, adds a critical layer of cybersecurity. The mitigation efforts include implementing role-based access control, regular system penetration testing, zero-trust principles, software checks and locks, and network segmentation between avionics and the Information Technology (IT) systems. The data loss or breach of liability risk describes the loss or compromise of operational data. The needed mitigation measures are securing cloud compliance frameworks and creating procedures for incident response and recovery.

5. Conclusion, Key Findings, and Future Improvements

A.E.R.I.S. offers a technically grounded and practically deployable approach to closing the predictive maintenance gap in legacy narrow-body aircraft. The system is built around a two-layer architecture: a Hybrid Wireless Sensor Network that combines self-powered MEMS vibration-temperature nodes with FBG strain sensors, and a ground-based Intelligent Solution Matrix. Together, these components show that condition-based monitoring can be added to aging Airbus A320ceo platforms with minimal structural modifications or interference with certified avionics.

The findings make it clear that the main limitation in current predictive maintenance is not the absence of sensor data, but the fragmentation of that data across OEM, operator, and MRO systems that do not communicate effectively. This is addressed directly through TSN interface adapters and a standardized data mapping pipeline, which consolidates disparate data streams into a unified, analysis-ready format.

From an implementation standpoint, Supplemental Type Certificate (STC) development remains the largest cost driver, estimated at \$5M–\$8M. However, even under conservative assumptions, the projected fleet-wide return on investment falls between 171% and 185%, with additional gains expected as the ISM's predictive models improve with real-world operational data. Importantly, the system is designed to operate strictly as a decision-support tool: all maintenance actions still require A&P sign-off, and built-in safety override logic ensures compliance with operational safety standards and FAA certification requirements.

As the system accumulates data over time, its predictive accuracy is expected to improve. At the same time, modular, open-standard architecture allows for the integration of additional sensors and expansion to other aircraft types without requiring a redesign of the core system.

Appendices

Appendix A: List of Abbreviations

Table 1: Abbreviation List

Abbreviation	Expansion
A.E.R.I.S.	Aircraft Enhanced Resilience Intelligence System
AOG	Aircraft on Ground
STC	Supplemental Type Certificate
DER	Directive Engineering Representatives
FAA	Federal Aviation Administration
ROI	Return on Investment
QAR	Quick Access Recorders
DAU	Data Acquisition Units
OEM	Original Equipment Manufacturer
MRO	Maintenance, Repair, Overhaul
WFD	Widespread Fatigue Damage
ECS	Environmental Control System
APU	Auxiliary Power Units
HUMS	Health and Usage Monitoring System
ACMS	Aircraft Condition Monitoring Systems
ECAM	Electronic Centralized Aircraft Monitoring
H-WSN	Hybrid Wireless Sensor Network
ISM	Intelligent Solution Matrix
IoT	Internet of Things
MEMS	Micro-Electromechanical Systems
PZT	Piezo-Electric Transducer
BLE	Bluetooth Low Energy
FBG	Fiber Bragg Grating
OTDR	Optical Time Domain Reflectometry
CMC	Central Maintenance Computer
TSN	Time Sensitive Networking
CMMS	Computer Maintenance Management System
A&P	Airframe and Powerplant
MCDU	Multifunction Control and Display Unit
MEL	Minimum Equipment List
FDR	Flight Data Recorder
OMS	Onboard Maintenance System
EHMS	Engine Health Monitoring System
MSG-3	Maintenance Steering Group-3
TRL	Technology Readiness Level
GIS	Geographic Information System
ROM	Rough Order Magnitude
IT	Information Technology

Appendix B: Tables

Table 2: Technology Readiness Level Assessment

Components	TRL	Purpose/Justification
Software/Data Integration		
H-WSN	5-6	These sensors and IoT networks are widely used in modern aircraft and even in some older models to provide real-time data. However, the suggested system that will be implemented will be done on a large scale thus needing a prototype and testing
Data Mapping	5-6	GIS mapping, a specific type of data mapping, plays a critical role in analyzing and managing aeronautical data but will need further testing
Intelligent Solution Matrix	4	This concept exists already and is in use however, this specific version will need research to prove feasibility. The creation and testing of a prototype will be required to analyze its effectiveness
Hardware		
MEMS vibration-temperature sensors	4-5	Condition based monitoring vibrational and thermal monitoring of gears, flaps, ECS, APU mounts. Self-energy harvesting feature uses vibration harvesting (PZT cantilever on wing) or thermoelectric from skin gradients, which is the proposed update of sensors. These two parts have yet to successfully prototyped but are in use separately. Sensors are considered for commercial CBM with TRL 7-8 and prototypes harvesting features of TRL 4-5.
FBG strain sensors	4-5	Distributed strain/load monitoring on wings, fuselage, and repairs. Modifying it with vibration harvesting via integrated PZT harvester and supercapacitors for duty cycle is an untested combination but has proven performance on their own. Sensors have been flight proven putting them at TRL 7-8, while harvesting features have lab prototypes with TRL 4-5.

Table 3: Major Cost Components for STC Development

Cost Element	Typical Share	Low End ($5M)	High End ($8M)
Engineering / Compliance	30–40%	$1.5M–$2M	$2.4M–$3.2M
DER approvals	20–30%	$1M–$1.5M	$1.6M–$2.4M
Flight testing	10–20%	$0.5M–$1M	$0.8M–$1.6M
Conformity & inspections	5–10%	$0.25M–$0.5M	$0.4M–$0.8M
FAA project management	5–10%	$0.25M–$0.5M	$0.4M–$0.8M
Program management / documentation	5–10%	$0.25M–$0.5M	$0.4M–$0.8M

Table 4: Hypothetical Fleet-Wide Implementation Cost Breakdown

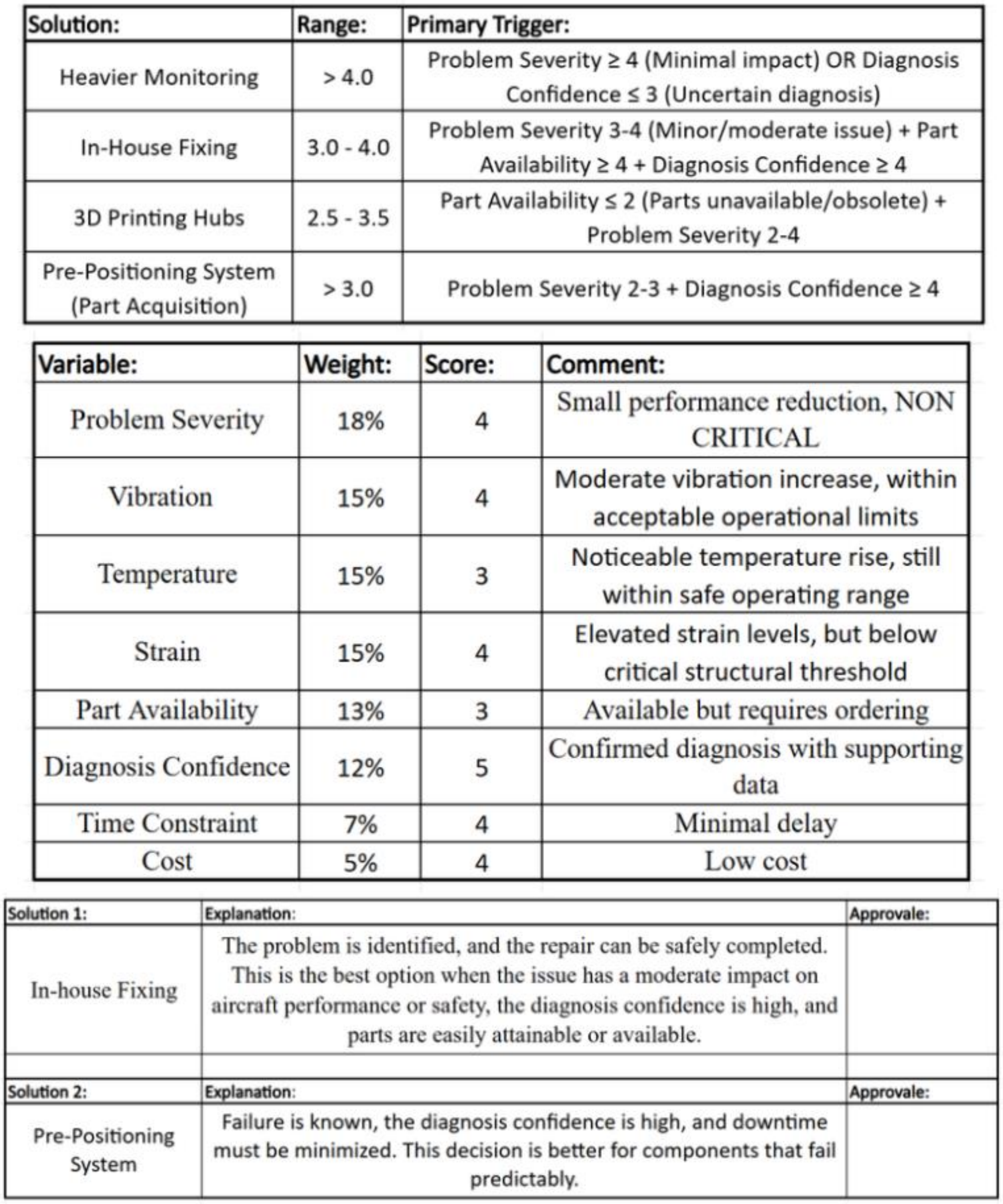
Component	**Hypothetical Costs**	**Description**
Retrofit Costs	$100,000–**$500,000**	Involves the equipment procurement, blueprint development, and installation costs
ISM and Grounded System	$300,000	Involves the development of the ISM software and necessary grounded components such as data mirroring and data mapping

Table 5: Hypothetical Total Costs for Fleet-Wide Implementation and ROI

Total Annual Savings	**Range End**	**Total Investment Cost**	**ROI**
$162,225,000	Low End	$56,800,000	185.61%
	High End	$59,800,000	171.28%

Appendix C: Figures

Figure 1: Intelligent Solution Matrix Chart



Solution:	Range:	Primary Trigger:
Heavier Monitoring	> 4.0	Problem Severity ≥ 4 (Minimal impact) OR Diagnosis Confidence ≤ 3 (Uncertain diagnosis)
In-House Fixing	3.0 - 4.0	Problem Severity 3-4 (Minor/moderate issue) + Part Availability ≥ 4 + Diagnosis Confidence ≥ 4
3D Printing Hubs	2.5 - 3.5	Part Availability ≤ 2 (Parts unavailable/obsolete) + Problem Severity 2-4
Pre-Positioning System (Part Acquisition)	> 3.0	Problem Severity 2-3 + Diagnosis Confidence ≥ 4

Variable:	Weight:	Score:	Comment:
Problem Severity	18%	4	Small performance reduction, NON CRITICAL
Vibration	15%	4	Moderate vibration increase, within acceptable operational limits
Temperature	15%	3	Noticeable temperature rise, still within safe operating range
Strain	15%	4	Elevated strain levels, but below critical structural threshold
Part Availability	13%	3	Available but requires ordering
Diagnosis Confidence	12%	5	Confirmed diagnosis with supporting data
Time Constraint	7%	4	Minimal delay
Cost	5%	4	Low cost

Solution 1:	Explanation:	Approvale:
In-house Fixing	The problem is identified, and the repair can be safely completed. This is the best option when the issue has a moderate impact on aircraft performance or safety, the diagnosis confidence is high, and parts are easily attainable or available.	
Solution 2:	**Explanation:**	**Approvale:**
Pre-Positioning System	Failure is known, the diagnosis confidence is high, and downtime must be minimized. This decision is better for components that fail predictably.	

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