SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V12I5P108

Volume 12 Issue 5, 70-80, May 2025
2025 Seventh Sense Research Group®

Review Article

Maintainability Improvement in Ageing Aircraft: A Critical Review of Evolving Strategies

Shaktiyavesh Nandan Pratap Singh[1], Rohitashwa Shringi[2], Manish Chaturvedi[3], Ajay Kumar[4]

[1,2,3]*Department of Mechanical Engineering, Rajasthan Technical University, Rajasthan, India.*
[4]*Department of CSET, Bennett University, Greater Noida, U.P. India.*

[1]*Corresponding Author : snpsingh.phd19@rtu.ac.in*

Received: 11 March 2025 Revised: 10 April 2025 Accepted: 09 May 2025 Published: 31 May 2025

Abstract - *The combination of longer functional periods for modern aircraft caused by economic needs and reliable design has generated a fast-growing number of ageing aircraft throughout global flight operations. A thorough assessment of maintenance methods becomes essential because of this modern aviation trend to guarantee aircraft airworthiness together with operational excellence. This review assesses contemporary research about ageing aircraft maintainability improvement through technological advances, data-based approaches and programmatic changes. The research analyzed 7 reference books and 21 military standards/ handbooks alongside 150 research papers and their related subjects on maintainability and its fields of study. Multiple research gaps emerge from systematic classifications that apply different methods to predict future directions for innovative research. The analysis exposes the complex problems caused by aircraft structural deterioration combined with technological aging and economic hardship, which require an integrated solution for longer aircraft operations. Multiple authors have contributed their research to maintainability and associated fields throughout the time span from 1981 to 2024, which this paper describes. The research discusses all present-day solution methods incorporating mathematical models, AI-based solutions and simulation techniques. Few empirical data and relevant solution approaches exist which support the maintenance requirements of aging military aircraft systems. The review implements systematic research approaches to combine present information before aiming at unanswered questions to guide future studies.*

Keywords - *Aviation, Maintenance, Reliability & Maintainability, Optimisation, AI.*

1. Introduction

Reliability and Maintainability (R&M) are two important aspects of maintenance in any industry or service operation. Over time, R&M's approach, thoughts and implementation of R&M have changed a lot. The importance of R&M is now taken into account, not only in the maintenance stage but also right from the planning process up to the production of something and then redesigning it. The mission mix can have an effect on executing the main mission, ensuring safety, systems, humans, and environment, and managing its costs, resources and human efforts. When research, innovations, and technologies improve, this allows for a better quality of work, higher efficiency, affordability, continued operations, and customer satisfaction, accomplishing the organisation's mission and further development. For this reason, it is important for an organisation to follow the latest approaches and models towards enhancing the maintenance aspect specific to Maintainability Improvement (MI). The role of MI in aviation is highly important and severe.

The aviation industry stands as the most difficult and important operational system worldwide. The time savings from distance reduction create beneficial opportunities for delivering needed resources (people, material, machines, business, societal help and military components) at necessary locations faster and simultaneously protect nations against aerial dangers. Flight safety rules and regulations receive strict enforcement in this specific domain, among all others. A mission of air operation needs comprehensive operational and maintenance management that follows the Standard Operating Procedures (SOPs) to achieve success. Any deviation will immediately create life-threatening situations that result in significant economic losses. The Federal Aviation Administration (FAA) USA, along with National Transportation Safety Board (NTSB), cited 12 instances of aircraft accidents caused by poor maintenance during the Year 1995 – 2001, according to [1]. When examining ageing aircraft conditions, the official definition leads to maintenance of aircraft reaching 75% of the maximum design lifespan, yet the Chinese Civil Aviation Administration defines such aircraft as ageing after 14 years of service [2]. The severe risks to safety and economics linked with aging military aircraft create an imperative situation that demands enhanced maintenance execution and management of air operations. Effective solutions for these issues depend on upgrading original maintenance practices, upgrading aircraft maintenance management systems in military aviation, reducing maintenance operation dead time while optimizing available resources, optimizing life cycle costs, enhancing demand monitoring methods and spare management protocols, improving operational planning effectiveness and delivering flight safety assurances. Research on these aspects as part of strategies has not been found, especially in military aviation, which is a major research gap. Since the MI includes finding suitable maintenance procedures that could achieve efficient, reliable and swift operational missions for military aircraft, therefore the objectives of this research are not only to focus on MI aspects in military aviation but also to explore solutions for minimizing several aging aircraft issues including reduction of :-

- Fault rectification analysis time in case of system failures.
- The time required for fault rectification repair starts after identifying and locating the source of the problem.
- Resources that are unavailable result in a delay time in operations.
- Life cycle costs of equipment.
- The skilled expertise of maintenance personnel decreases in level.
- Safety levels suffer degradation while maintenance activities take place.
- Outdated maintenance practices and dependability.

The aviation industry relies heavily on aging aircraft because the exceptional longevity of modern aircraft structures meets economic pressures. Reliability evidence shows that aircraft present maintenance complexity because operational wear combined with environmental factors affects their condition. This paper combines existing scholarly work on MI for ageing aircraft to evaluate successful methods and recommend future research directions. This paper delivers relevant information to all professionals operating in research development to utilize MI-based technologies throughout their design-to-operation lifecycle process.

2. Literature Review

Maintainability refers to how easily and efficiently an item can be kept in or restored to a specified condition during maintenance. This process is carried out by personnel with designated skill levels, using established procedures and resources appropriate for each maintenance and repair level. Additionally, maintainability encompasses the likelihood that an item can be maintained or restored to that specified condition under similar circumstances [3]. Maintainability can be measured in several ways. The most known is Mean Time To Repair (MTTR), described in the following Equation (1): -

$$\mathrm{MTTR} = \int_0^\infty t.h(t)dt = \int_0^\infty (1 - H\,(t)dt \tag{1}$$

Where h (t) is a probability density function, and H (t) is the probability that a repair will be accomplished within time (t) [4]. The factors affecting Maintainability establish critical relationships among vital factors, which provide a deep insight into the maintainability concept as a whole in Figure 1**.**

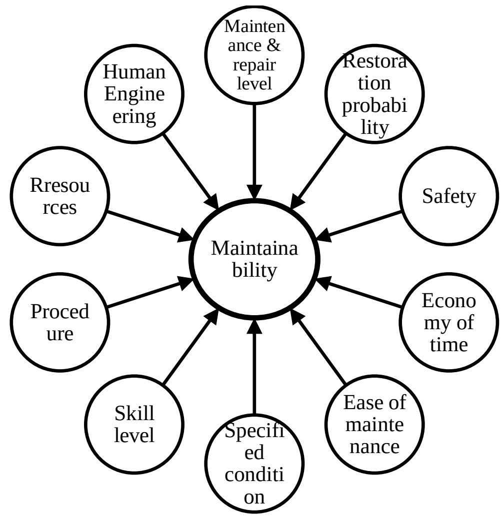

Fig. 1 Factors affecting Maintainability

The improvement of maintainability creates better availability outcomes for specified equipment operations under specific conditions. Figure 2 demonstrates how maintainability affects various organizational factors within aviation businesses.

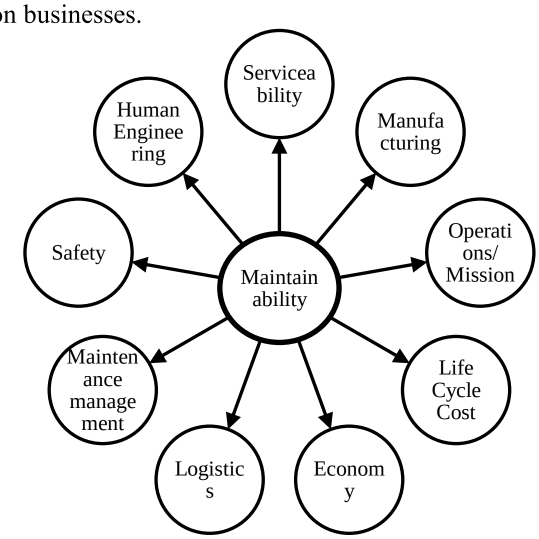

Fig. 2 Effect of Maintainability

The multifaceted challenges of ageing aircraft with respect to maintainability are as follows: -

2.1. Structural Integrity and Fatigue

An ageing airframe is a problem since so much of it is about extending structural degradation and extending corrosion from loss of coordination failures and environmental damage. This risk, however, leads to the simultaneous development of numerous structural component cracks, resulting in widespread structural integrity problems, i.e. Widespread Fatigue Damage (WFD). Monitoring and stopping fatigue damage failures were used to test and evaluate damage tolerance analysis [5]. To detect structural defects, early stages need to be implemented using advanced Non-Destructive Testing (NDT) such as computerized tomography, eddy current testing and phased array ultrasonic testing. Therefore, the realization of the most important requirement is to realize an effective Structural Health Monitoring (SHM) system capable of continuous evaluation in real time. Research works in aging aircraft corrosion focus on creating effective prevention systems by developing improved coating solutions and sealants [6].

2.2. Technological Obsolescence and System Integration

The avionics components and mechanical systems that support ageing aircraft face mounting maintenance challenges because they utilize outdated technology that has reached its end of support life. The difficulty of sourcing replacement parts, along with the integration needs of modern technologies, makes it essential to adopt forward-looking obsolescence management solutions. The study by [7] examined flight system obsolescence by showing why aircraft manufacturers need to redesign components and add new technologies. A complete examination of advanced flight management systems and communication systems needs to take place before certifying their digital integration capabilities. Newer systems integrated into legacy systems might lead to unpredictable problems with these older systems.

2.3. Economic Constraints and Operational Efficiency

Safe operations of aging aircraft create extensive financial burdens that force operators to find suitable balance points between security and dependability, and economic feasibility. The maintenance expenses dramatically increase during the aircraft lifetime because operators need to implement improved maintenance techniques. The authors developed affordable maintenance methods through Condition-Based Maintenance (CBM) and Reliability Centered Maintenance (RCM) [7]. The identified strategies work to reduce maintenance actions that are not needed while adapting maintenance planning for the most efficient results. Using lean maintenance approaches directly leads to better operational performance together with cost reduction efforts.

2.4. Human Factors and Maintenance Personnel

Operations of aging aircraft depend on personnel who complete advanced training and hold professional skills appropriate to their roles. Research conducted on aviation maintenance human factors systems has established that training programs along with ergonomic principles need effective communication methods [8]. Staff maintenance workers in the aviation industry encounter skill development challenges because of their growing age. Knowledge management systems, together with simulation-based training programs, will help decrease the impact these challenges create.

2.5. Research Gaps

The brief comparative analysis on the relationship merits of the presented paper against selected similar publications are as below: -

- Analysed that safety, maintainability, reliability, testability and risk are correlative with respect to parts failure. Failure and risk calculations need to be carried out for quality aircraft. This is applicable for commercial aircraft as a theoretical measures. However, the same needs to be validated against military aircraft.
- Proposed Artificial Intelligence (AI) for allocation of maintainability in aircraft at the design phase and using a feed-forward neural network to predict the aircraft‘s component maintainability. The approach was theoretical and applicable to commercial aircraft.
- [9] proposed that military capability, Reliability, Maintainability and Supportability (RMS) should be considered equally important to the capability of military organisations. However, this was only a paper in the context of military aviation. However, the strategies for MI need to be addressed. Therefore, the presented study mitigates the existing research gaps and may benefit from adding to the current research in this field.

3. Materials and Methods

An exhaustive literature search through a scientific data mining approach has been carried out with keywords related to MI in civil/ military aviation over e-journals of Emerald Insight, Science Direct, IEL online, Wiley, World E-Book Library, Research Gate and Google Scholar.

The decisive reviews on MI and related studies as carried out by various researchers have been illustrated in the successive section. The following steps achieve the comprehensive study of the literature review:

- Exploring the maintenance concept with respect to maintainability to know what reference books/authors talk about the above concepts?
- Identification of latest trends post review of previous contributions on MI and related studies till 2024.
- Classification of various approaches used in MI and related studies.
- Classification of maintenance models/ solutions based on maintainability and related tasks as per the guidance of MIL-HDBK- 470A [3].
- Strategies inferred for MI based on critical analysis
- Research directions explored based on outcomes

Therefore, a four-phase data collection from 7 reference books, 21 military standards/ handbooks and 150 research papers based on MI in aviation are considered and refinement methodology is followed (at least title/ full abstract/ detailed study as per the phases) as per the following block diagram as depicted in Figure 3.

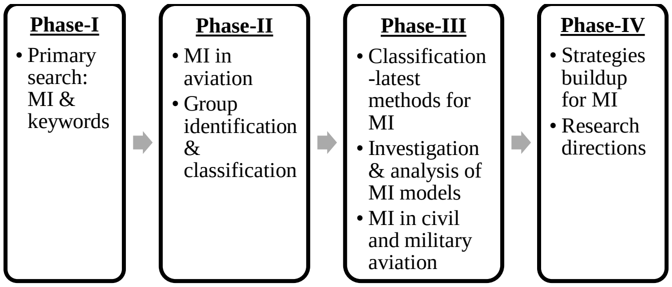

Fig. 3 Literature's Search

4. Results and Discussion

4.1. Latest Trends

Extensive literature searches have been carried out on MI and associated studies. It is found that the number of available research papers is very minimal in the context of military aircraft (18 out of 150); this may be due to dependency over OEM based solution approaches, lack of empirical data, lack of research and development-based activities at the field level, lack of sharing of information in respect of innovations or ideas, lack of financial and motivational support for research.

In order to explore this further, a wider search has been carried out, keeping a holistic view of the maintainability concept in general Aircraft Maintenance Management (AMM). The following observations are made: -

- The research in the MI and related studies area has seen growing trends in the past 5 years. The main reason is the inclusion of AI-driven approaches. In the era of 2002 – 2024, most of the research papers talk about the modernization of classical maintenance management and related approaches through computer-based maintenance management, along with the inclusion of reliability, availability, maintainability, and other related studies as a whole. The basic concepts and importance of the maintenance studies are carried out in the era of 1992 – 2002.
- A total of 70 different approaches have been identified. It has been observed that the highest research was found in maintenance optimization and related concept areas, with 10% of the research. The subsequent approaches are Failure Mode Effect Analysis (FMEA) or Critical Analysis (FMECA) (5%), Reliability Techniques/ Tools (4%), Human Factor (4%), RMS (4%), Discrete Event Simulation (4%) & No Fault Found (NFF) (3%). The major distribution of approaches (with more than 3% literatures) with respect to no. of literatures is depicted in Figure 4.
- The various latest methods explored for MI in the aviation sector are consolidated in Figure 5. The occurrence of research on MI through the aspects of maintenance optimization is high on the rise, followed by FMEA and other reliability tools.

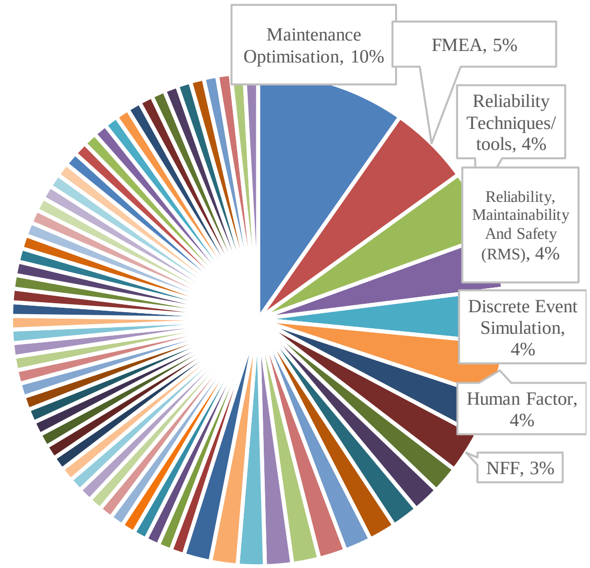

Fig. 4 Approaches and No. of literatures

- The reviewed literature has also been classified with respect to the applicability of various approaches like a practical application of the proposed research, i.e. holistic or singular, literature evidence, i.e. theoretical or empirical, and whether the application is found in a military context, commercial context, or the general maintenance management. It is important to note here that the maintainability and the related area of research are abundant in the commercial sector and/ or general maintenance management area, whereas very minimal in military aviation with 18% literature. It is also observed that the maximum literature is based on theoretically based approaches, whereas only 2% of the literature is empirically based and with singular approaches, it is 29%.
- In order to narrow down the research area, further classification based on maintainability and related tasks as per MIL – HDBK – 470A [3] has been followed. This particular classification is used to identify the types of research that have emerged in a particular area of concern, i.e. design, analysis, test, and others with respect to maintainability. It is found that there is much literature that exists which uses a combination of different approaches as one. Therefore, the author introduces a new category in the list of above military standards, i.e. *Mixed or Integrated Approach*. It is observed that the intermixing of different approaches is emerging as a new trend in order to improve maintainability as applied in different sectors in AMM. It has also been observed that more research has been found in the modeling and simulation category, while very few have been found in the Failure Reporting Analysis & Corrective Action System (FRACAS). The details are tabulated in Table 1.

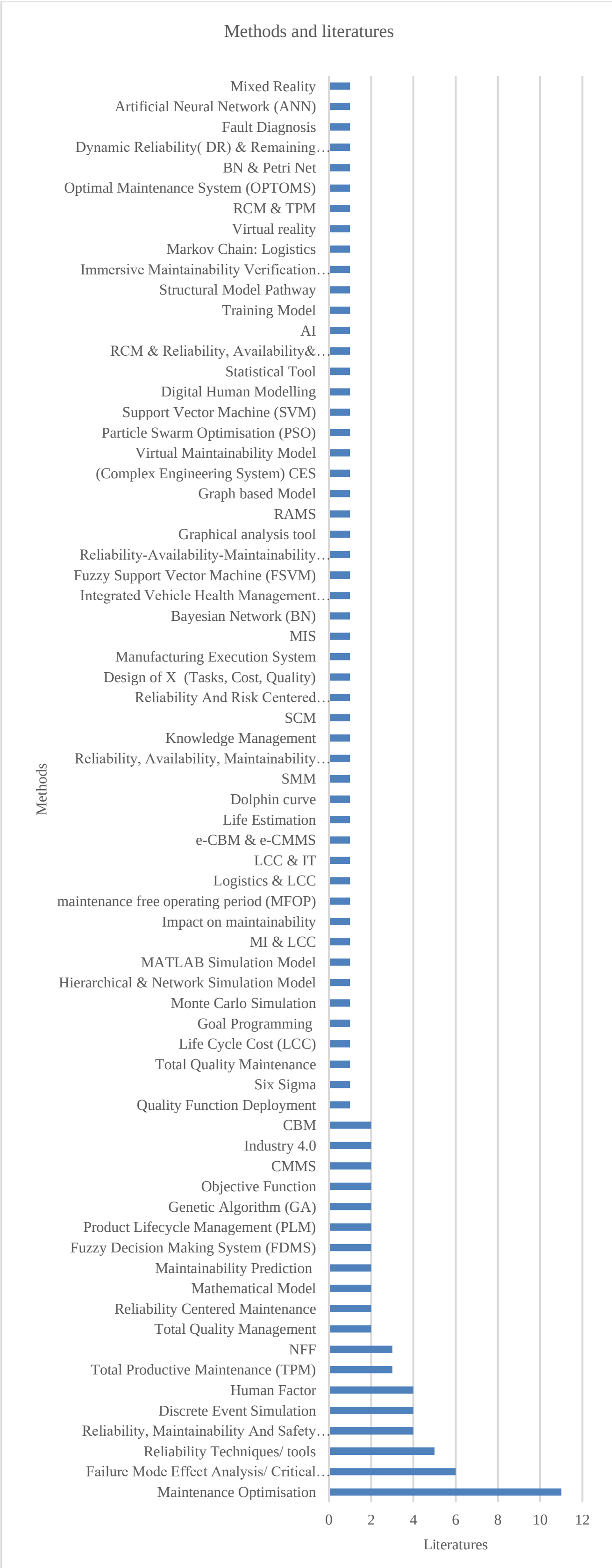

Fig. 4 Methods and No. of literatures

Table 1. Maintainability categories and approaches

Category	Approaches
Testability and Diagnostics	1. NFF [10] 2. Bayesian Network (BN) [11]
Design Reviews	1. Industry 4.0 [12] 2. RCM & TPM [13]
Environmental Characterization	Maintenance culture [14]
Supplier Control	1. Performance-based logistics [15] 2. Markov chain, Gradient search method [16]
Human Engineering	Digital human modeling [17]
Human Factors	1. Computerized maintenance management system (CMMS) [18] 2. Human factor analysis and classification system [19] 3. Mixed Reality [20]
FMECA	Reliability centered maintenance (RCM) & Fuzzy decision-making system (FDMS) [21]
Failure Reporting Analysis & Corrective Action (FRACAS)	1. Data cleaning, Log-rank test, BN, Pareto diagram, MTTR [22] 2. Case Studies for repairable systems [23]
Life Cycle Planning	1. LCC & IT [24] 2. TPM [25] 3. RUL [26] 4. Integrated framework with sustainable development [27]
Modeling & Simulation	1. Virtual maintainability model [28] 2. Mathematical model on false alarm [29] 3. Simulation model based on hierarchical and network models [30] 4. Genetic Algorithm [31] 5. MATLAB simulation model using Queuing Network [32] 6. Opportunistic principle towards Optimal maintenance system (OPTOMS) [33] 7. Design of 'X' [34] 8. Goal programming mathematical model [35] 9. AI/ Artificial neural network [36]
Predictions	Prediction based on aircraft feedback information [37]
Repair Strategies.	Strategic maintenance management [38]
Quality Function Deployment	QFD [39]

Allocations	AI [40]
Verification test	Virtual reality [41]
Evaluation.	R&M [42]
Statistical Process Control	TQM & process management [43]
Mixed or Integrated Approach	1. Industry 4.0, Big Data analytics & Internet of Things (IoT) [44] 2. Safety, maintainability, reliability, testability and risk analysis [45] 3. BN & Petri Net (PN) [46]

4.2. Strategies for Maintainability Improvement. The following strategies are developed that need to be considered for implementation: -

4.2.1. Advanced Maintenance Technologies. The following aspects are to be considered

- *Prognostics and Health Management (PHM)*. PHM uses data analytics models to process data retrieved from different sensors. The system delivers information about upcoming failure events to optimize maintenance schedule decisions. The research carried out by [47] shows that PHM provides effective methods for aircraft reliability improvements while cutting down maintenance expenses. The predictive analysis of PHM successfully implements Machine Learning (ML) models through ensembled regression models and various ML models-based neural networks and support vector machines. Research groups are implementing these models for Remaining Useful Life (RUL) predictions of aeroengines.
- *Non-Destructive Testing (NDT).* The phased-array ultrasound combined with digital radiography testing is essential in improving NDT procedures. Ultrasonic testing for detecting fatigue cracks in aircraft structures has advanced, according to findings from [48]. Aircraft structures become constantly monitored by integrating the SHM systems with NDT methodologies.
- *Digital Twins*. The digital twin's technology provides great tools for evaluating aircraft maintenance operations in a simulated aircraft environment. The application of digital twin technology for aircraft maintenance planning optimization together with performance improvement is studied in depth by [49]. Digital twins help users determine how maintenance decisions influence aircraft reliability while they assess multiple maintenance approaches.

4.2.2. Data-Driven Maintenance. The following aspects have emerged: -

- *Data Analytics*. Operations from aerial flights, records of maintenance activities, and information gathered from sensor systems produce extensive amounts of data in aviation. The integrated techniques of ML and Statistical modeling optimize the maintenance process along with the failure prediction. Research by [50] demonstrates how data mining techniques operate in predictive maintenance schemes.
- *Condition-Based Maintenance (CBM)*. The approach of CBM tracks aircraft components through monitoring, which leads to the performance of maintenance tasks according to need. The research conducted by [7] shows that implementing Condition-Based Maintenance produces more value for money than conventional time-based maintenance approaches. For CBM to function, a sensor system must work together with data acquisition instruments and analytical software.
- *Reliability-Centered Maintenance (RCM)*. Aircraft maintenance strategies under the RCM system begin by detecting critical functions of the aircraft system to develop operational approaches that sustain reliability. The research by [51] shows that RCM establishes advantages for aircraft safety alongside maintenance cost reductions. RCM approaches failure mode analysis to evaluate results from failure determination and then picks suitable maintenance functions.

4.2.3. Improved Maintenance Programs

The following aspects have emerged

- *Aging Aircraft Management Programs (AAMPs)*. Such programs present extensive solutions for managing aircraft risks that emerge due to aircraft ageing. AAMP development guidelines emerged from studies carried out by [52]. The maintenance program includes stronger inspections together with modifications to the structure and replacements of aircraft components.
- *Enhanced Training and Education*. Specialized training needs to be provided to maintenance personnel who handle the maintenance of ageing aircraft. The study conducted by [53] explains how training along with teamwork contributes to aviation maintenance success. Training programs must provide specialized instructions about ageing aircraft challenges, emphasising detecting corrosion and fatigue assessment and obsolescence management methods.
- *Improved Communication and Collaboration*. For proper upkeep of aging aircraft operators must collaborate effectively with manufacturers as well as regulatory agencies together with other stakeholders. The work of [54] demonstrates why safety culture, together with proper communication systems, represents critical elements for aerospace safety. Enhancing communication allows stakeholders to exchange operational excellence approaches while building collaborative service practices.

4.3. Research Directions

Based on the subject review, the following directions need to be considered: -

4.3.1. Integration of Artificial Intelligence (AI)

Artificial intelligence supports the prediction of component breakdowns through aircraft-sourced health information obtained from sensors. The predictive and proactive maintenance concept strengthened by this technology enhances both safety and maintenance efficiency as well as life cycle costs and reduces system downtime. [55]. AI can play a significant role in automating maintenance tasks, analyzing complex data, and predicting failures. Evolutionary research needs to concentrate on building AI-powered maintenance systems that support ageing aircraft.

4.3.2. Development of Advanced Sensor Technologies

Presently, the sensors used in the aerospace field face challenges of improvisation in material quality and structural design. The implementation of integrated circuits alongside advanced mathematical models together with AI protocols and deployment error mitigation strategies represents the solution for the field [56]. The combination of wireless sensor networks together with Micro-Electromechanical Systems (MEMS) serves as a suitable technology for real-time aircraft structure and system monitoring. Developing sturdy, reliable sensor systems for extreme operating environments needs research attention.

4.3.3. Optimization of Maintenance Planning and Scheduling

The use of e-Conservative models together with Monte Carlo sampling through hybrid simulation-optimization methods allows the extraction of dependable, robust solutions despite disturbances. The methodology handles traditional probabilistic constraints by producing optimal results that match all specified conservatism requirements and uncertainty criteria [57]. The optimization process includes two techniques known as simulation and mathematical programming for planning maintenance procedures and setting schedules. Researchers must create efficient algorithms to schedule maintenance work and assign available resources.

4.3.4. Development of Standardized Maintenance Procedures

The Fleet Maintenance Decision-Making Model (FMDM) implements CBM and maintenance optimization algorithm based on the propagation of yeast (OA/PY) method for maintenance procedure enhancement [58]. Research needs to be done to investigate better maintenance procedures that will help achieve continual failproof aircraft operations. The research must create standardized protocols for aircraft maintenance of ageing planes through inspections alongside component replacement and repair processes.

4.3.5. Focus on Sustainable Maintenance Practices

The sustainability of aircraft MRO consists of safe and ethical operation through technological growth along with environmental impact reduction which serves to benefit all stakeholders [59]. Research must adopt sustainable maintenance practices because environmental concerns are elevating in priority. The company implements environmentally friendly cleaning solutions, component recycling, and energy-efficient maintenance process development throughout their operations.

4.3.6. Challenges and Proposed Solutions

The solutions against various challenges pertaining to maintainability are mentioned in Table 2.

Table 2. Challenges and solutions

Challenges	Solutions
Structural Integrity and Fatigue	SHM with phased-array ultrasound combined with digital radiography NDT
Technological Obsolescence and System Integration	AAMP, AI/ML, Wireless sensor network with MEMS, PHM and Digital Twin.
Economic Constraints and Operational Efficiency	AI/ ML, Data-driven based maintenance, FMDM, Sustainable practices,
Human Factors and Maintenance Personnel	Enhanced training program considering obsolesce management, improved communication, and collaboration.

4.4. Comparative Analysis

A comparative analysis of previous studies based on a similar field with respect to the proposed study is carried out and mentioned in Table 3.

Table 3. Comparative Analysis of Previous Studies

Research Study	Scope	MI Aspects	Method	Techniques Used	Strengths	Limitations	Evaluation
[10]	Procedure	No Fault Found (NFF) in Maintenance	Theoretical	Case Study	Remedial Measures Against Maintenance Issues	Procedural Delay, Lack of Automation	Singular Approach
[19]	Procedure	Human Errors	Theoretical	Case Study	Practical Aspects	Limited Scope with respect to Situational Awareness. Training and	Singular Approach

						Skill Improvement.	
[20]	System	Maintenance & Training	Theoretical	Mixed Reality	Good Knowledge	Practical Implementation	Holistic Approach
[60]	Procedure	Human Factors	Theoretical	Review Paper	Stress on Human aspects	Scientific Analysis	Singular Approach
[61]	System	Uncertainty	Theoretical	Review Paper	Framework Strategies	Scientific Analysis	Holistic Approach
Proposed Study	System	All MI Aspects	Scientific and Exploratory	Data Analytics	Applied Expert Knowledge on System Domain integrated with Data Analytics covering Strategies and Future Directions.	Designed for Ageing Aircraft Field	Expert Scientific Reviews with a Holistic Approach

5. Conclusion

Any aviation field depends heavily on maintainability as a fundamental necessity. The military availability of aircraft for operations depends directly on this core and susceptible factor. Operating aged aircraft demands complex solutions to deal with multiple complexities. Any military aircraft requiring operational status needs extensive maintenance services for preservation. Aeronautical engineers, techno managers, and aircraft maintenance technicians provide sincere service at every stage of aircraft maintenance to achieve mission-critical objectives. Team involvement becomes essential when operating with aged military aircraft persists. The decreasing number of available spare parts leads to increased material and structural failures, which make existing maintenance procedures incompatible with OEM guidelines. Due to procurement procedures together with financial limitations and political unwillingness most developing countries find it challenging to adopt new military aircraft or change their existing fleet. The condition becomes grave when field-level failures occur because they compromise the mission's primary objectives. The military aviation field needs heightened investments so that all such relevant countries obtain enhanced benefits from the researchers' work. Minimal research regarding military aircraft maintenance appears in this literature review. A substantial assortment of literary material evaluates aircraft maintenance through commercial aviation frameworks but focuses only on standard AMM practices. Most cases reveal minimal or absent empirical data or field data, which would provide both research insights and close to correct solutions for military aircrafts maintenance methods. The use of contemporary modeling technologies and artificial intelligence systems concentrates on the design procedure of equipment during manufacturing operations. Only a small number of relevant methods exist to support aircraft maintenance conducted at field locations, which require numerous deliberations. A 'Nil' solution method could examine viable maintenance improvements that use local field resources to support aging military aircraft. The research gaps were resolved through the content in Section 4. The research scope expansion is achieved through MIL – HDBK – 470A [3] military standard analysis, which outlines future research areas in design, analysis, test and other categories. The examined literature demonstrates how maintainability improvements are achieved through technological progress, data-driven techniques, and program advancement methods. The combined efforts of PHM systems with NDT processes using analytic solutions enhance aircraft reliability and reduce maintenance expenses. These strategies need comprehensive execution, considering the specific issues with ageing aircraft and systems. The focus of research efforts should be on building AI-enabled software for maintenance needs and enhancing sensor equipment while standardizing system procedures. The real-world maintenance application in aviation with respect to various case studies and potential cost savings may further be examined as part of future studies. The aviation industry will maintain operational safety and efficiency for aging aircraft through proper challenge management along with the implementation of technological advancements.

References

[1] Levin, A. “Accidents caused by maintenance”, 2001. Retrieved from https://www.faa.gov.in/media.

[2] Wang Yonggang, and Long Honglang, “Summary and Analysis of the Ageing Aircrafts’ Failure,” *Procedia Engineering*, vol. 17, pp. 303-309, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[3] MIL-HDBK-470A, *Department of Defense Handbook: Designing and Developing Maintainable Products and Systems*, vol. 1, pp. 1-716, 1997. [Google Scholar] [Publisher Link]

[4] Charles E. Ebeling, *An Introduction to Reliability and Maintainability Engineering*, McGraw-Hill, pp. 1-486, 2004. [Google Scholar] [Publisher Link]

[5] R.P. Swift et al., “Micro-Mechanical Modeling of Perforating Shock Damage,” *SPE International Conference and Exhibition on Formation Damage Control*, Lafayette, Louisiana, pp. 1-13, 1998. [CrossRef] [Google Scholar] [Publisher Link]

[6] R. Winston Revie, and Herbert H. Uhlig, *Corrosion and Corrosion Control*, 4th ed., John Wiley & Sons, pp. 1-512, 2008. [Google Scholar] [Publisher Link]

[7] Andrew K.S. Jardine, Daming Lin, and Dragan Banjevic, “A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance,” *Mechanical systems and Signal Processing*, vol. 20, no. 7, pp. 1483-1510, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[8] Scott A. Shappell, and Douglas A. Wiegmann, “*A Human Error Analysis of General Aviation Controlled Flight Into Terrain Accidents Occurring between 1990–1998*,” DOT/FAA/AM-03/4, U.S. Department of Transportation, Technical Report, pp. 1-21, 2003. [Google Scholar] [Publisher Link]

[9] WGCdr J. Robinson, “*Reliability, Maintainability and Supportability of the Royal Canadian Air Force Future Fighter Capability*,” Canadian Forces College, Report, pp. 1-13, 2016. [Publisher Link]

[10] Chris Hockley, and Laura Lacey, “A Research Study of no Fault Found (NFF) in the Royal Air Force,” *Procedia CIRP*, vol. 59, pp. 263-267, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[11] Susana Ferreiro et al., “Application of Bayesian Networks in Prognostics for a New Integrated Vehicle Health Management Concept,” *Expert Systems with Applications*, vol. 39, no. 7, pp. 6402-6418, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[12] Sanja Lazarova-Molnar, and Nader Mohamed, “Reliability Assessment in the Context of Industry 4.0: Data as a Game Changer,” *Procedia Computer Science*, vol. 151, pp. 691-698, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[13] Marcello Braglia, Davide Castellano, and Mosè Gallo, “A Novel Operational Approach to Equipment Maintenance: TPM and RCM Jointly at Work,” *Journal of Quality in Maintenance Engineering*, vol. 25, no. 4, pp. 612-634, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[14] Kym Fraser, “Facilities Management: The Strategic Selection of a Maintenance System,” *Journal of Facilities Management*, vol. 12, no. 1, pp. 18-37, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[15] Martin Holmbom, Bjarne Bergquist, and Erik Vanhatalo, “Performance-Based Logistics – An Illusive Panacea or a Concept for the Future?,” *Journal of Manufacturing Technology Management*, vol. 25, no. 7, pp. 958-979, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[16] Mansik Hur, Burcu B. Keskin, and Charles P. Schmidt, “End-of-Life Inventory Control of Aircraft Spare Parts Under Performance Based Logistics,” *International Journal of Production Economics*, vol. 204, pp. 186-203, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[17] J Sanjog et al., “Towards Virtual Ergonomics: Aviation and Aerospace,” *Aircraft Engineering and Aerospace Technology*, vol. 87, no. 3, pp. 266-273, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[18] Hadi Balouei Jamkhaneh et al., “Impacts of Computerized Maintenance Management System and Relevant Supportive Organizational Factors on Total Productive Maintenance,” *Benchmarking: An International Journal*, vol. 25, no. 7, pp. 2230-2247, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[19] Prasanna Illankoon, Phillip Tretten, and Uday Kumar, “A Prospective Study of Maintenance Deviations Using HFACS-ME,” *International Journal of Industrial Ergonomics*, vol. 74, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[20] Silvia Liberata Ullo et al., “A Step toward the Standardization of Maintenance and Training Services in C4I Military Systems with Mixed Reality Application,” *Measurement*, vol. 138, pp. 149-156, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[21] Rajiv Kumar Sharma, and Pooja Sharma, “System Failure Behavior and Maintenance Decision Making Using, RCA, FMEA and FM,” *Journal of Quality in Maintenance Engineering*, vol. 16, no. 1, pp. 64-88, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[22] Cornel Bunea et al., “Application of Modern Reliability Database Techniques to Military System Data,” *Reliability Engineering & System Safety*, vol. 93, no. 1, pp. 14-27, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[23] Sukhwinder Singh Jolly, and Bikram Jit Singh, “An Approach to Enhance Availability of Repairable Systems: A Case Study of SPMs,” *International Journal of Quality & Reliability Management*, vol. 31, no. 9, pp. 1031-1051, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[24] David Sherwin, “A Review of Overall Models for Maintenance Management,” *Journal of Quality in Maintenance Engineering*, vol. 6, no. 3, pp. 138-164, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[25] Benjamin S. Blanchard, "An Enhanced Approach for Implementing Total Productive Maintenance in the Manufacturing Environment," *Journal of Quality in Maintenance Engineering*, vol. 3, no. 2, pp. 69-80, 1997. [CrossRef] [Google Scholar] [Publisher Link]
[26] Liang Zeming, Gao Jianmin, and Jiang Hongquan, "A Maintenance Support Framework Based on Dynamic Reliability and Remaining Useful Life," *Measurement*, vol. 147, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[27] S. Keivanpour, and D. Ait Kadi, "A Sustainable Approach to Aircraft Engine Maintenance," *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 977-982, 2015. [CrossRef] [Google Scholar] [Publisher Link]
[28] Pradeep Kumar, and Calvin C. Varkey, "*Designing Line Replaceable Units from the Maintainability*," White Paper Maintainability Quest Global, Report, pp. 1-8, 2012. [Google Scholar] [Publisher Link]
[29] Ahmed Raza, and Vladimir Ulansky, "Modelling of False Alarms and Intermittent Faults and Their Impact on the Maintenance Cost of Digital Avionics," *Procedia Manufacturing*, vol. 16, pp. 107-114, 2018. [CrossRef] [Google Scholar] [Publisher Link]
[30] K. Sadananda Upadhya, and N.K. Srinivasan, "Availability Estimation Using Simulation for Military Systems," *International Journal of Quality & Reliability Management*, vol. 29, no. 8, pp. 937-952, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[31] Qinming Liu, and Wenyuan Lv, "Multi-Component Manufacturing System Maintenance Scheduling Based on Degradation Information Using Genetic Algorithm," *Industrial Management & Data Systems*, vol. 115, no. 8, pp. 1412-1434, 2015. [CrossRef] [Google Scholar] [Publisher Link]
[32] Zineb Simeu-Abazi, Maria Di Mascolo, and Eric Gascard, "Queuing Network-Based Methodology for Designing and Assessing Performance of Centralized Maintenance Workshops," *Journal of Manufacturing Technology Management*, vol. 25, no. 4, pp. 510-527, 2014. [CrossRef] [Google Scholar] [Publisher Link]
[33] Hasnida Ab-Samat, and Shahrul Kamaruddin, "Development of Opportunistic Maintenance Policy towards Optimal Maintenance System (OPTOMS) Model: A Case Study," *Journal of Quality in Maintenance Engineering*, vol. 26, no. 1, pp. 129-165, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[34] Anoop Arun Desai, and Anil Mital, "Improving Maintainability of Products through the Adoption of a Comprehensive DfX Methodology," *The International Journal of Industrial Engineering: Theory, Applications and Practice*, vol. 17, no. 2, pp. 103-114, 2010. [CrossRef] [Google Scholar] [Publisher Link]
[35] Yuttapong Pleumpirom, and Sataporn Amornsawadwatana, "Multiobjective Optimization of Aircraft Maintenance in Thailand Using Goal Programming: A Decision-Support Model," *Advances in Decision Sciences*, vol. 2012, pp. 1-17, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[36] J. Izquierdo, A. Crespo Márquez, and Uribetxebarria, "Dynamic Artificial Neural Network-Based Reliability Considering Operational Context of Assets," *Reliability Engineering & System Safety*, vol. 188, pp. 483-493, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[37] Wan Mohd Sufian Wan Husain, "Maintainability Prediction for Aircraft Mechanical Components Utilizing Aircraft Feedback Information," *Applied Mechanics and Materials*, vol. 225, pp. 528-533, 2012. [CrossRef] [Google Scholar] [Publisher Link]
[38] Albert H.C. Tsang, "Strategic Dimensions of Maintenance Management," *Journal of Quality in Maintenance Engineering*, vol. 8, no. 1, pp. 7-39, 2002. [CrossRef] [Google Scholar] [Publisher Link]
[39] Daniel Carnerud, "Exploring Research on Quality and Reliability Management Through Text Mining Methodology," *International Journal of Quality & Reliability Management*, vol. 34, no. 7, pp. 975-1014, 2017. [CrossRef] [Google Scholar] [Publisher Link]
[40] Davut Yılmaz, and İbrahim Özkol, "A New Method for Aircraft Maintainability Allocation," *International Journal of Mechanical Engineering and Robotics Research*, vol. 7, no. 1, pp. 93-99, 2018. [CrossRef] [Google Scholar] [Publisher Link]
[41] Ziyue Guo et al., "Using Virtual Reality to Support the Product's Maintainability Design: Immersive Maintainability Verification and Evaluation System," *Computers in Industry*, vol. 101, pp. 41-50, 2018. [CrossRef] [Google Scholar] [Publisher Link]
[42] NATO-ARMP-7, "*NATO R&M Terminology Applicable to ARMPs*," pp. 1-32, 2008. [Google Scholar] [Publisher Link]
[43] T.J. Sharp, and C.A. Ervin, "Improving Reliability and Maintainability through Process Management," *Annual Reliability and Maintainability Symposium 1992 Proceedings*, Las Vegas, NV, USA, pp. 93-97, 1992. [CrossRef] [Google Scholar] [Publisher Link]
[44] R. Roy et al., "Continuous Maintenance and the Future – Foundations and Technological Challenges," *CIRP Annals*, vol. 65, no. 2, pp. 667-688, 2016. [CrossRef] [Google Scholar] [Publisher Link]
[45] Yuanyuan Guo et al., "Risk Assessment of Complex System Based on Man-Machine-Environment," *2019 Prognostics and System Health Management Conference (PHM-Paris)*, Paris, France, pp. 228-231, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[46] Sohag Kabir, and Yiannis Papadopoulos, "Applications of Bayesian Networks and Petri Nets in Safety, Reliability, and Risk Assessments: A Review," *Safety Science*, vol. 115, pp. 154-175, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[47] Jay Lee et al., "Recent Advances and Trends in Predictive Manufacturing Systems in Big data Environment," *Manufacturing Letters*, vol. 1, no. 1, pp. 38-41, 2014. [CrossRef] [Google Scholar] [Publisher Link]
[48] Eric Lindgren et al., "Ultrasonic Plate Waves for Fatigue Crack Detection in Multi-Layered Metallic Structures," *Proceedings of Health Monitoring of Structural and Biological Systems 2007*, San Diego, California, United States, pp. 1-12, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[49] Michael Grieves, "*Digital Twin: Manufacturing Excellence through Virtual Factory Replication in Exploring Digital Frontier*," Digital Twin White Paper, pp. 1-8, 2016. [Google Scholar] [Publisher Link]

[50] Foster Provost, and Tom Fawcett, "Data Science and its Relationship to Big Data and Data-Driven Decision Making," *Big Data*, vol. 1, no. 1, pp. 51-59, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[51] Eric R. Ziegel, "Reliability-Centered Maintenance," *Technometrics*, vol. 38, no. 1, pp. 1-87, 1996. [CrossRef] [Google Scholar] [Publisher Link]

[52] "*Federal Aviation Administration*," Aging Aircraft Program, FY 2010 Performance and Accountability Report, pp. 1-140, 2010. [Google Scholar] [Publisher Link]

[53] Eduardo Salas et al., "The Science of Training and Development in Organizations: What Matters in Practice," *Psychological Science in the Public Interest*, vol. 13, no. 2, pp. 74-101, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[54] Sidney Dekker, *Drift into Failure: From Hunting Broken Components to Understanding Complex Systems*, 1st ed., CRC Press, pp. 1-234, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[55] Kondala Rao Patibandla, "Predictive Maintenance in Aviation Using Artificial Intelligence," *Journal of Artificial Intelligence General Science*, vol. 2, no. 1, pp. 326-333, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[56] Alizadeh, Saltykova, and Novinzadeh, "Optimizing MEMS Based Navigation Sensors for Aerospace Vehicles," *RUDN Journal of Engineering Researches*, vol. 25, no. 1, pp. 57-74. 2024. [CrossRef] [Google Scholar] [Publisher Link]

[57] Hani Shahmoradi-Moghadam, Nima Safaei, and Seyed Jafar Sadjadi, "Robust Maintenance Scheduling of Aircraft Fleet: A Hybrid Simulation-Optimization Approach," *IEEE Access*, vol. 9, pp. 17854-17865, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[58] Lin Lin, Fang Wang, and Bin Luo, "An Optimization Algorithm Inspired by Propagation of Yeast for Fleet Maintenance Decision Making Problem Involving Fatigue Structures," *Applied Soft Computing*, vol. 85, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[59] Gita Andhika Swastanto, and Mary E. Johnson, "Exploratory Study of Sustainability Practices in Worldwide Major Aircraft Maintenance, Repair, and Overhaul Companies," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2678, no. 11, pp. 1060-1078, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[60] Mohammad Sheikhalishahi, Liliane Pintelon, and Ali Azadeh, "Human Factors in Maintenance: A Review," *Journal of Quality in Maintenance Engineering*, vol. 22, no. 3, pp. 218-237, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[61] John Ahmet Erkoyuncu et al., "An Innovative Uncertainty Management Framework to Support Contracting for Product-Service Availability," *Journal of Service Management*, vol. 25, no. 5, pp. 603-638, 2014. [CrossRef] [Google Scholar] [Publisher Link]