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## Advanced Maintenance Strategies for Gas Turbine Engines: A Review of Condition Based, Predictive, and Risk-Based Approaches

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**Abstract:** Gas turbine engine maintenance plays an important role in maintaining reliability, safety, and operational efficiency in aviation and power generation systems. This review analyzes the development of maintenance strategies from Time Based Maintenance (TBM) to Condition Based Maintenance (CBM), predictive maintenance, and risk based decision approaches. The study was conducted through a review of journal articles, technical reports, and case studies related to engine performance, maintenance scheduling, and health monitoring systems. The literature was evaluated based on maintenance objectives, data requirements, implementation complexity, and operational outcomes such as cost efficiency, downtime reduction, and failure prediction capability. The results show that TBM is still effective for standardized maintenance planning but has limitations in reflecting actual engine conditions. In contrast, CBM and predictive maintenance improve maintenance effectiveness through sensor based monitoring, prognostic health management, and machine learning assisted fault detection. Risk based approaches, including Partially Observable Markov Decision Process (POMDP) models, provide better support for maintenance optimization under uncertain conditions. However, challenges remain in terms of infrastructure costs, data integration, and compatibility with regulatory requirements. Overall, advanced maintenance strategies have significant potential to improve the efficiency and reliability of gas turbine engine operations.

**Keywords:** Gas Turbine Maintenance, Predictive Maintenance, Condition Based Maintenance, Risk Based Optimization, Reliability

### Introduction

Gas turbine engines are widely used in aviation and power generation because of their high power to weight ratio, operational flexibility, and thermal efficiency. In aeronautical applications, however, engine reliability is not only an economic concern but also a direct safety requirement. Recent studies show that degradation in turbine blades, bearings, combustors, and compressor components significantly affects engine reliability and increases the probability of unscheduled maintenance events, making predictive maintenance essential for modern aero engines [1]. This is further exemplified by the analysis of CFM56-3 engines in Indonesian aviation operations, which emphasizes that reliability centered maintenance is essential to mitigate unscheduled maintenance costs[2]. Consequently, maintenance strategy plays a central role in preserving engine airworthiness, reliability, and life cycle efficiency.

Conventional maintenance practice has long relied on fixed interval or time-based maintenance (TBM), in which inspection and overhaul activities are scheduled according to predefined operating hours or cycles. Although this approach is straightforward and compatible with regulatory maintenance planning, it does not always reflect the actual condition of engine components.

Recent advances in condition-based maintenance (CBM) and predictive maintenance have introduced more adaptive approaches by integrating sensor data, engine health monitoring, and data driven diagnostic models. These approaches enable maintenance decisions to be linked more closely to the physical condition of the engine, thereby improving fault detection and supporting Remaining Useful Life (RUL) prognostics for predictive maintenance [4]. Evidence from prior studies also shows that engine performance degradation is strongly influenced by operating and material conditions. For example, analysis of the



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CFM56-3-B1 turbofan engine on the Boeing 737-300 showed that material friction and environmental factors contributed to a measurable reduction in thermal efficiency of 9.59%, demonstrating the importance of maintenance strategies that are sensitive to actual engine deterioration [5].

Despite this progress, the literature remains fragmented. Existing studies often discuss CBM, predictive maintenance, risk-based maintenance, Critical Path Method (CPM), or digital twin technologies separately, while limited attention has been given to how these approaches can be interpreted within a unified maintenance decision framework for gas turbine engines. In particular, the practical challenge lies in balancing maintenance cost, operational reliability, downtime, and risk under uncertain degradation conditions. Models such as Partially Observable Markov Decision Processes (POMDP) have been proposed to support such decision making, yet their integration into large scale industrial and aeronautical maintenance practice is still limited [6].

Therefore, this article aims to review and compare advanced maintenance strategies for gas turbine engines by focusing on four major aspects: (1) the limitations of conventional TBM, (2) the role of CBM and predictive maintenance in detecting degradation and improving maintenance timing, (3) the contribution of risk based and probabilistic models such as POMDP to maintenance optimization, and (4) the managerial relevance of supporting tools such as CPM, maintenance management systems, and digital monitoring concepts. By synthesizing these perspectives, this review seeks to provide a clearer analytical basis for maintenance planners, airline operators, and maintenance, repair, and overhaul (MRO) organizations in selecting appropriate strategies for reliable and cost-effective engine maintenance.

The remainder of this paper is organized as follows. The Methods section explains the review design, literature selection, and analytical criteria. The Results and Discussion section compares the characteristics and practical implications of the identified maintenance strategies. Finally, the Conclusion summarizes the main findings, limitations, and future directions for advanced gas turbine engine maintenance.

## Method

This study applies a structured review approach combining qualitative synthesis and comparative analysis to examine maintenance strategies for gas turbine engines in aeronautical and related industrial applications. The objective of the method is not to perform a statistical meta-analysis, but to identify major maintenance approaches, compare their characteristics, and evaluate their relevance to engine reliability, maintenance efficiency, and operational risk.

### Literature Collection and Selection

The literature used in this review was collected from published journal articles, conference papers, technical reports, and selected academic final projects relevant to gas turbine engines and maintenance strategy development. The scope of the review includes studies discussing engine performance degradation, maintenance scheduling, condition monitoring, predictive analytics, and decision support models. The reviewed literature was limited to documents published between 2021 and 2025 to ensure the relevance and up-to-date development of research in the field of gas turbine engine maintenance. In addition, the sources of the articles and scientific references were obtained from reputable academic databases, primarily Google Scholar and Scopus, to ensure the credibility, quality, and academic validity of the reviewed studies. Keywords used in the selection process included gas turbine maintenance, aircraft engine maintenance, condition-based maintenance, predictive maintenance, prognostic health management, digital twin, risk-based maintenance, and POMDP. These keywords were selected to ensure that the collected studies represent both traditional and modern maintenance strategies applied in gas turbine engines[7].

The inclusion criteria covered studies that: (1) addressed gas turbine or aero engine maintenance, (2) reported conceptual, methodological, or practical findings related to maintenance planning or health monitoring, and (3) provided analytical relevance to performance indicators such as reliability, downtime, cost efficiency, or degradation assessment. Additionally, The review includes studies discussing gas-path deterioration, compressor efficiency loss, thermal fatigue, and vibration-related failures that affect aero engine reliability and maintenance performancee [8]. According to recent findings, strict adherence to OEM-recommended maintenance schedules significantly improves gas turbine reliability by reducing unexpected failures, minimizing downtime, and extending operational lifespan through timely inspections and preventive maintenance [9]. Studies were excluded when they lacked direct relevance to maintenance decision making, focused only on general mechanical systems



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without turbine specific implications or provided insufficient methodological detail. Representative sources included investigations involving the IAE V2500, Rolls-Royce M250-C20B, CFM56-3C1, CFM56-5B, and Dart 7 MK 534-2. Recent studies have also demonstrated that artificial intelligence based prediction models, particularly exhaust gas temperature (EGT) forecasting techniques, can support trustworthy prognostic maintenance systems by enabling early detection of abnormal engine conditions and improving maintenance decision accuracy [10].

## Comparative Evaluation of Effectiveness

The comparative analysis synthesized both qualitative and quantitative findings reported in prior studies, particularly those related to maintenance cost reduction, downtime reduction, Mean Time Between Failures (MTBF), and system availability. Because the reviewed studies used different datasets, operational environments, and reporting formats, the numerical values presented in this paper should be interpreted as indicative ranges derived from literature trends rather than as directly normalized universal benchmarks. For this reason, the analysis emphasizes comparative direction and engineering relevance rather than strict cross study equivalence.

Studies addressing probabilistic decision making, especially POMDP based and risk based models, were reviewed to assess how uncertainty, inspection intervals, and operational consequences were incorporated into maintenance planning [6]. This step enabled the comparison of conventional maintenance logic with more adaptive and uncertainty aware strategies

## Identification of Research Gaps and Limitations

The review also identified research and implementation gaps found across the literature. These include the difficulty of integrating CBM systems with original equipment manufacturer (OEM) procedures, the high cost of digital infrastructure, limited standardization of maintenance data, and the restricted use of advanced AI driven decision models in certified aeronautical environments. In addition, the review recognizes potential limitations inherent in literature-based analysis, including publication bias, variation in case study quality, inconsistency in performance metrics, and differences in engine type and operating conditions. Therefore, conclusions drawn from the reviewed studies must be understood within the context of these methodological constraints [11]. Recent studies also indicate that limited operational data availability remains a major challenge in developing accurate intelligent degradation prediction models for gas turbine engines, particularly in applications where sensor coverage and long term maintenance records are insufficient [12].

## Integration of Advanced Maintenance and Analytical Methods

In addition to the literature based and comparative analysis approach, this study also adopts a managerial perspective utilizing the Critical Path Method (CPM) to map out critical activities in the gas turbine maintenance process. The procedure begins with collecting data on the stages of work, identifying interdependencies among activities, and calculating the duration for each stage. Forward pass and backward pass techniques are applied to determine the earliest and latest possible start and finish times for each activity, allowing the identification of critical paths. This analysis supports minimizing downtime and optimizing resource allocation during gas turbine engine maintenance at both overhaul and major component installation levels, such as engine removal and reinstallation[13].

Furthermore, this research incorporates principles of maintenance management systems, focusing on the integration of project management and material provisioning strategies[14]. This approach emphasizes planning, organizing, monitoring, and controlling maintenance activities to align with production schedules and airworthiness regulations. A well-structured maintenance management system enables workload balancing, inspection scheduling, and logistics control for component availability. The methodology is based on preventive maintenance, predictive maintenance, and condition based maintenance (CBM) principles, ensuring safety compliance and quality assurance throughout the maintenance cycle[13].

Additionally, prior studies have highlighted methods for assessing engine component performance through mathematical correlation between physical parameters and performance indicators. For example, correlation analysis is employed to evaluate the effect of high-pressure compressor (HPC) rotor clearance variations on Exhaust Gas Temperature Margin (EGTM). The process involves measuring actual rotor clearance, calculating deviations from manufacturer specified minimum clearance, and estimating its impact on EGT using a simplified correlation equation. This approach is crucial for predicting performance degradation due to wear or damage, enabling more accurate preventive maintenance actions [15].

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## Results And Discussion

The comparative review shows clear differences in the operational characteristics and expected benefits of the evaluated maintenance strategies. Time Based Maintenance (TBM) remains the most established approach because it is simple to administer, compatible with scheduled maintenance programs, and relatively easy to standardize. However, the literature consistently indicates that TBM offers limited flexibility in responding to actual engine condition. As a result, its reported benefits in cost and downtime control are generally modest when compared with more adaptive strategies. In this review, the low improvement range associated with TBM should be understood as reflecting its preventive but no cognition sensitive nature rather than a failure of the method itself.

To strengthen the comparative results, the reviewed documents were classified according to the main evaluation parameters established in this study, namely maintenance objective, data requirement, implementation complexity, and operational outcomes. The classification provides a clearer basis for interpreting the differences among TBM, CBM, predictive maintenance, and risk-based maintenance strategies. Table 1 summarizes the reviewed documents and their contribution to the analysis of gas turbine engine maintenance strategies.

**Table 1. Summary of Reviewed Documents Based on Evaluation Parameters**

No.	Ref.	Year	Main Focus / Strategy	Engine / System Context	Data Requirement	Implementation Complexity	Main Evaluation Parameter	Key Finding / Contribution
1	[1]	2022	Predictive maintenance and RUL-based scheduling	Aircraft engine	RUL prognostics, alarm data, maintenance schedule	High	Failure prediction, downtime, maintenance scheduling	Predictive maintenance improves scheduling decisions, but imperfect RUL estimation can affect maintenance accuracy.
2	[2]	2024	Reliability-centered maintenance	CFM56-3 / Boeing 737-500	Failure record, reliability data, maintenance history	Medium	Reliability, unscheduled maintenance, maintenance cost	Reliability analysis helps identify engine maintenance needs and supports reduction of unscheduled maintenance.
3	[3]	2023	Condition-Based Maintenance	Aviation maintenance system	Sensor data, inspection data, health monitoring data	Medium-High	Reliability, maintenance responsiveness, implementation barriers	CBM improves condition awareness, but faces challenges in data integration and organizational readiness.
4	[4]	2022	RUL predictive maintenance using GRU	Aircraft engine	Time-series engine condition data	High	RUL prediction, failure forecasting	GRU-based models support degradation trend prediction and improve predictive maintenance decision making.
5	[5]	2025	Engine performance degradation analysis	CFM56-3-B1 / Boeing 737-300	Engine performance parameters, operating condition data	Medium	Thermal efficiency, performance degradation	Engine degradation affects thermal efficiency, showing the need for condition-sensitive maintenance strategies.

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No.	Ref.	Year	Main Focus / Strategy	Engine / System Context	Data Requirement	Implementation Complexity	Main Evaluation Parameter	Key Finding / Contribution
6	[6]	2024	Risk-based maintenance and POMDP model	Gas turbine engine components	Failure probability, inspection interval, operational consequence data	High	Risk, cost optimization, decision uncertainty	POMDP supports maintenance decision making under uncertainty and offers strong optimization potential.
7	[7]	n.d.	Vibration testing	CFM56-7B turbofan engine test cell	Vibration measurement data	Medium	Vibration behavior, fault indication	Vibration monitoring provides useful information for early detection of abnormal engine conditions.
8	[8]	2023	Gas-path deterioration and reliability assessment	Aeroengine gas path	Stochastic degradation data, gas-path performance indicators	High	Reliability, degradation observation	Gas-path deterioration modelling supports reliability assessment and degradation-based maintenance planning.
9	[9]	2025	Field maintenance practice and reliability metrics	Gas turbine / field maintenance context	Maintenance practice records, reliability metrics	Medium	Reliability, MTBF, downtime	OEM-recommended maintenance practices improve reliability and reduce unexpected failures.
10	[10]	2022	AI-based EGT prediction	Safety-critical aeroengine application	Exhaust Gas Temperature data, AI model input	High	EGT prediction, safety, prognostics	AI-based EGT prediction supports early abnormal condition detection and trustworthy prognostic maintenance.
11	[12]	2025	Intelligent performance degradation prediction	Light-duty gas turbine engine	Limited operational data, degradation indicators	High	Degradation prediction, data limitation	Intelligent models can predict degradation, but limited operational data reduces prediction robustness.
12	[13]	2025	Critical Path Method for maintenance execution	RR Trent 700 / Airbus A330	Maintenance activity duration, task dependency data	Medium	Downtime, resource allocation, maintenance duration	CPM identifies critical maintenance activities and supports downtime reduction during engine removal and installation.
13	[14]	2023	Maintenance management and safety risk	Aircraft airframe maintenance	Risk data, maintenance planning data, operational control data	Medium	Safety risk, maintenance management, compliance	Integrated maintenance management supports safety compliance, scheduling control, and material availability.

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No.	Ref.	Year	Main Focus / Strategy	Engine / System Context	Data Requirement	Implementation Complexity	Main Evaluation Parameter	Key Finding / Contribution
14	[15]	2021	HPC rotor clearance and EGTM analysis	CFM56-7	Rotor clearance data, EGTM data	Medium	EGT margin, component wear, performance degradation	Rotor clearance variation affects EGT margin and can be used as an indicator for preventive maintenance decisions.
15	[16]	2023	Sensor data for aircraft turbine engine maintenance education	Aircraft turbine engine	Sensor data, turbine engine operating parameters	Medium	Fault detection, maintenance learning, condition monitoring	Sensor-based monitoring helps transform engine parameter deviations into useful maintenance information.
16	[18]	2025	Improved gas turbine operation and emissions	Aircraft engine operation	Engine operation data, emission-related parameters	Medium	Operational efficiency, CO <sub>2</sub> emission reduction	Improved operation and maintenance practices contribute to better combustion efficiency and reduced emissions.
17	[19]	2021	Gas turbine jet engine monitoring and maintenance lessons	Gas turbine jet engine	Monitoring data, maintenance experience	Medium	Monitoring effectiveness, reliability, maintenance practice	Continuous engine monitoring supports maintenance improvement and strengthens reliability-oriented decision making.

Condition-Based Maintenance (CBM) provides a more responsive alternative by linking maintenance action to observed engine condition. Through sensor inputs, inspection data, and health monitoring trends, CBM improves the ability to detect abnormal behaviour before failure occurs. Compared with TBM, CBM generally shows better performance in reducing unnecessary maintenance actions and shortening disruption caused by avoidable unscheduled events. From an engineering perspective, the use of sensor-based monitoring systems enables measurable parameter deviations such as vibration, temperature, and pressure variations to be transformed into actionable maintenance information for aircraft turbine engines. This approach is particularly important in modern maintenance practices because continuous sensor data acquisition supports early fault detection, improves maintenance decision making, and enhances the reliability of gas turbine engine operations [16], [17].

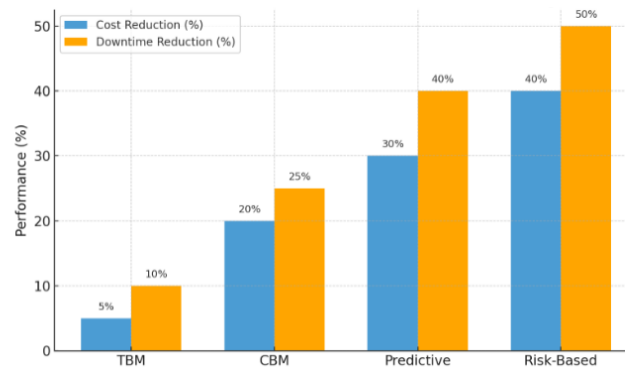
Predictive maintenance extends CBM by combining condition monitoring with data driven forecasting models. The literature reviewed in this study indicates that predictive maintenance can achieve higher failure prediction capability, often reported in the range of 80-90%, while also supporting greater reductions in maintenance cost and downtime than TBM and basic CBM. These improvements are not solely due to the use of artificial intelligence, but to the underlying engineering value of predicting degradation before it reaches an operationally critical threshold. Models such as LSTM and other machine learning methods are particularly effective in capturing temporal patterns in engine behaviour, making them suitable for trend-based fault development in gas turbine systems. In practical applications, improvements in gas turbine operational standards and enhanced maintenance practices contribute not only to engine reliability but also to the reduction of aircraft carbon dioxide emissions through more efficient combustion performance and optimized engine operation in accordance with established aviation standards [18], [6].

Risk based maintenance strategies, including those supported by POMDP models, represent the most analytically advanced category identified in this review. Their principal strength lies in incorporating uncertainty, probability of failure, and operational consequences into the maintenance decision process. Unlike TBM, which follows schedule logic, or CBM, which reacts to observed condition, risk-based models attempt to determine the most economically and operationally justified maintenance

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action under incomplete information. This explains why such approaches are frequently associated in the literature with the highest potential cost savings and downtime reductions. However, their practical implementation remains limited because they require substantial computational modelling, reliable prior probability structures, and maintenance data of sufficient quality to support decision optimization [6].

The comparative trend summarized in Figure 1 indicates that the progression from TBM to CBM, predictive maintenance, and risk-based approaches corresponds to a gradual increase in analytical sophistication and potential operational benefit. This trend can be interpreted as a shift from schedule-oriented maintenance toward condition-aware and decision-optimized maintenance. Figure 1 therefore should not be read merely as a descriptive ranking, but as an illustration of how increasingly data-rich approaches improve the ability to detect degradation, prioritize intervention, and reduce uncertainty in maintenance planning.



**Figure 1** Effectiveness of Gas Turbine Maintenance Strategies

From a practical standpoint, these findings are highly relevant for airlines and MRO organizations. For operators with limited digital infrastructure, CBM may represent the most realistic transition step because it can improve maintenance responsiveness without the full complexity of predictive or probabilistic systems. For large fleets or high-utilization engines, predictive maintenance offers stronger value by reducing unscheduled downtime and improving planning accuracy for labour, materials, and shop visits. Risk-based models may be most beneficial in high-cost decision environments, such as major engine maintenance planning, where uncertainty and consequence severity justify more advanced optimization methods. In this context, tools such as CPM also become important because maintenance effectiveness is influenced not only by fault detection quality but also by execution efficiency during removal, inspection, repair, and reinstallation processes [13].

Digital twin concepts further strengthen this transition by enabling virtual representation of engine condition in near real time. Their engineering relevance lies in combining physics-informed understanding with operational data, thereby increasing confidence in maintenance decision-making. Even so, implementation barriers remain substantial. These include high capital expenditure, limited data standardization across fleets, integration difficulties with legacy engines, and the need to align advanced analytics with airworthiness and maintenance documentation requirements. Accordingly, although advanced maintenance strategies outperform conventional methods in many reviewed studies, their adoption depends on technical maturity, organizational readiness, and regulatory compatibility.

Overall, the results confirm that data-driven and probabilistic maintenance strategies offer stronger potential for improving reliability, cost efficiency, and operational continuity in gas turbine engine maintenance. However, the review also shows that their superiority is conditional upon the availability of robust data systems, engineering validation, and practical implementation frameworks that can be used by operators in real maintenance environments.

## Conclusions

This study reviewed advanced maintenance strategies for gas turbine engines based on relevant academic and technical documents published mainly between 2020 and 2025. The review shows that gas turbine engine maintenance has shifted from conventional Time-Based Maintenance (TBM) toward more adaptive approaches, particularly Condition-Based Maintenance (CBM), predictive maintenance, and risk-based maintenance. TBM remains useful for standardized maintenance planning, but it has limitations because it does not fully reflect the actual condition of engine components.

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The main finding of this review is that CBM and predictive maintenance provide stronger support for maintenance decision making because they use engine condition data, sensor monitoring, and degradation trends to detect potential failures earlier. Risk-based maintenance further strengthens this process by considering uncertainty, operational consequences, and maintenance cost in selecting the most appropriate maintenance action. Therefore, advanced maintenance strategies have greater potential to improve reliability, reduce unscheduled downtime, and support more efficient gas turbine engine maintenance than conventional schedule-based approaches.

However, their implementation still depends on the availability of reliable data, digital infrastructure, technical capability, and compatibility with aircraft maintenance regulations. Future research should focus on developing a practical and standardized implementation framework that can help airlines and MRO organizations apply CBM, predictive maintenance, and risk-based maintenance in real operational environments.

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