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Reliability-Based Reassessment of Starter-Generator Preventive Maintenance Intervals on ATR 72-212A Aircraft Using Operational Removal Data

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ABSTRACT

This paper re-assesses the preventive maintenance interval of starter-generator part number 8260-124 installed on ATR 72-212A aircraft using operational removal data from Airline X between 2019 and 2024. A quantitative case-study approach was applied to 65 removal records, comprising 39 scheduled and 26 unscheduled removals. The analysis included failure-mode classification, Pareto analysis, statistical distribution fitting, Mean Time to Failure estimation, survival analysis, Component Removal Rate, and Mean Time Between Unscheduled Removal. Brush wear was identified as the dominant failure mode, accounting for 53.8% of unscheduled removals. The lognormal distribution provided the best fit to the Time Since Installation data, with an adjusted Anderson–Darling statistic of 0.746 and a correlation coefficient of 0.989. The estimated MTTF was 907.022 flight hours, substantially below the existing 1,200-flight-hour maintenance interval, while the survival probability declined to 51.6% at 900 flight hours and 13.1% at 1,000 flight hours. These findings indicate that the current interval provides insufficient preventive margin. Therefore, an 800-flight-hour interval is recommended to reduce brush-related deterioration, unscheduled removals, and associated operational disruptions.

KEYWORDS: *ATR 72-212A, Preventive Maintenance Interval, Reliability Analysis, Starter-Generator, Unscheduled Removal.*

NOMENCLATURE

AFML	Aircraft Flight Maintenance Log
AMM	Aircraft Maintenance Manual
BBC	Brush and Bearing Change
CMM	Component Maintenance Manual
CRR	Component Removal Rate
D/T	Defect or Trouble Indication
FH	Flight Hours (cumulative flight time exposure)
MTBUR	Mean Time Between Unscheduled Removals
MTTF	Mean Time to Failure
NH	High-pressure spool rotational speed
RCM	Reliability-Centered Maintenance
R(t)	Reliability or survival probability at operating time
S/N	Serial Number
t	Component operating time or age
TSI	Time Since Installation

1. INTRODUCTION

Aircraft operational reliability is strongly influenced by the health and continuity of its electrical power system, since this system supports essential aircraft functions, flight instruments, anti-icing equipment, and cabin services. In turboprop regional aircraft such as the ATR72-212A, the electrical system includes direct current, alternating current, and variable-frequency AC networks, in which the starter generator functions as both an engine starter and a DC generator. Because of this dual role, degradation or failure of the starter generator may directly affect dispatch reliability, flight regularity, and maintenance cost efficiency [1], [2].

From an airline maintenance perspective, starter generator failure is not merely a component-level technical event, but an operational issue with broader consequences. The data indicate repeated technical disruptions associated with starter generator part number 8260-124 on ATR72-212A aircraft, including unscheduled removals and operational disturbances such as delay, return to apron, and aircraft-on-ground situations. Such events indicate that the existing maintenance interval may not fully reflect the actual degradation behavior of the component in service.

The practical challenge in aircraft maintenance is to determine whether a component should continue to follow the existing scheduled maintenance interval or whether its interval should be adjusted based on observed reliability behavior. In this case, the issue becomes more important because the current maintenance program includes a brush bearing change task at a fixed interval, while field data show that many units are removed before reaching that scheduled limit. This condition indicates a possible mismatch between scheduled maintenance policy and actual time-to-failure

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behavior under operational conditions [3], [4].

Previous studies have shown that starter generator failures are often associated with brush degradation, zero output voltage, and other electrical or mechanical defects affecting aircraft operation. A previous study on ATR 72-600 reported that starter generator malfunction may directly affect aircraft operability, while another study on aircraft starter-generator maintenance found that brush-related failure modes were among the most dominant component problems [5], [6]. Additional studies on aircraft rotating electrical machines have also shown that brush, commutator, bearing, and temperature-related degradation are significant reliability drivers in service [7], [8].

In the present case, the dataset shows that brush worn out was the most dominant failure category, accounting for 53.8% of the recorded unscheduled removal cases, exceeding other causes such as engine cannot start, bearing wear, and DC generator fault. This finding indicates that the brush subsystem is the critical maintenance driver within the observed failure population. In other words, the reliability problem is not distributed evenly across all internal starter-generator elements, but is concentrated in one dominant degradation mode that can be used as a basis for maintenance interval reassessment. This observation is also consistent with previous studies indicating that brush-related deterioration is frequently a major source of starter-generator reliability loss [6], [7]. From a methodological perspective, reliability analysis provides a rational framework to quantify component behavior using failure-time data such as Time Since Installation (TSI), Mean Time To Failure (MTTF), failure trend, and reliability function [9], [10]. Rather than relying only on nominal schedule limits, this approach allows maintenance decisions to be supported by actual operational evidence.

In this paper, the observed TSI data were evaluated using statistical distribution identification, and the selected model indicated that the average failure occurrence was substantially below the currently scheduled 1200 flight-hours interval. This means that maintaining the existing interval without review may continue to expose the operator to avoidable unscheduled removals and associated operational penalties. Therefore, the significance of this paper lies in its attempt to bridge practical airline maintenance data with reliability-based decision support. Accordingly, this paper aims to analyze the dominant failure cause of starter generator part number 8260-124 installed on ATR72-212A aircraft, evaluate its reliability characteristics based on operational removal data, and propose a more effective scheduled maintenance interval to reduce the risk of unscheduled removal and associated operational disruption. By doing so, the paper is expected to provide a practical reliability-based reference for maintenance planning of starter-generator components in regional turboprop aircraft operations.

2. THEORETICAL BACKGROUND

2.1 Starter Generator in Aircraft Electrical Power Systems

In aircraft electrical power architecture, the starter generator is a critical rotating electrical machine that performs two principal functions. During engine start, it operates as a starter motor to provide the mechanical torque required to rotate the engine. After the engine reaches the required speed, the same unit changes its function and operates as a generator to supply electrical power to the aircraft system. This dual-function characteristic makes the starter generator operationally significant, because its degradation may affect both engine starting capability and onboard electrical power continuity [1], [2].

In the ATR72 aircraft family, the starter generator is part of the direct current electrical generation system. Its operational role is therefore directly linked to the availability of essential aircraft electrical supply during normal operation (Figure 1). Since the component works under repeated electrical, thermal, and mechanical loading, it is exposed to cumulative degradation over time. Such degradation may involve brush wear, commutator deterioration, bearing wear, and other internal mechanical-electrical interactions that can eventually reduce component performance and reliability [1], [7].

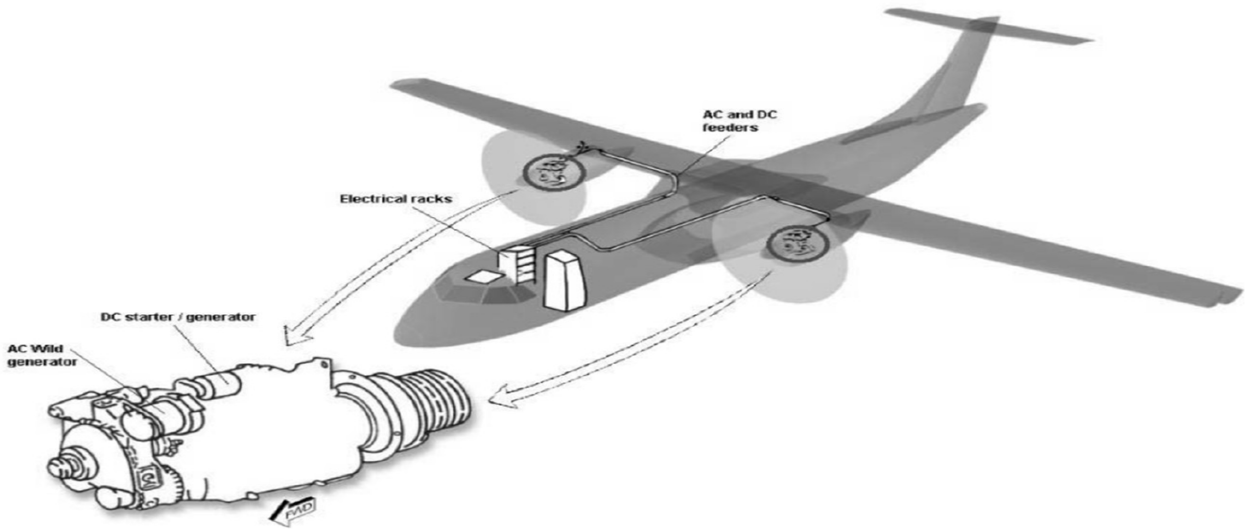

Figure 1: Location of starter generator in ATR72 aircraft electrical system

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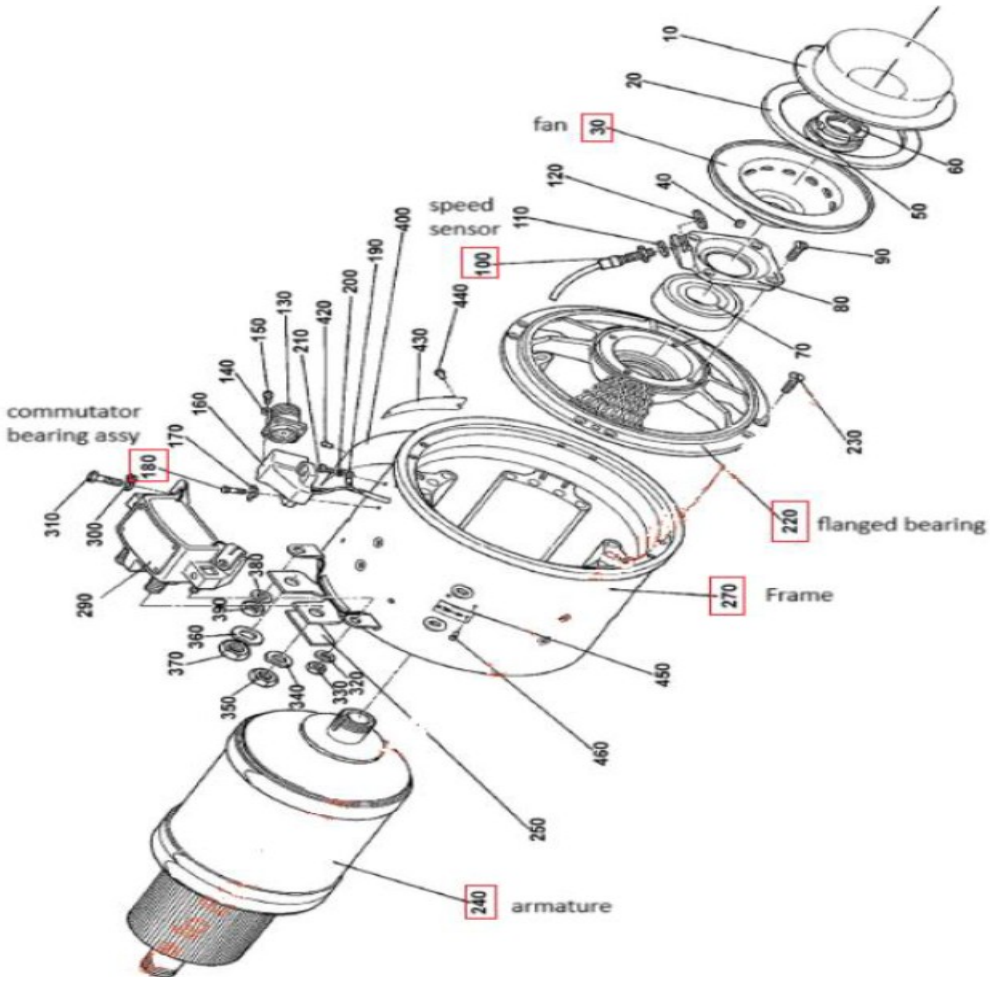

Figure 2: Main parts of starter generator

To support the engineering understanding of this component, the internal configuration of the starter generator should also be considered. The major internal parts include the frame, flanged bearing, commutator bearing assembly, armature, speed sensor, and fan (Figure 2). These parts work together as an integrated electro-mechanical system, and degradation in one part may influence the performance and durability of the entire unit. In particular, wear-prone elements such as the brush and commutator interface are especially important because their deterioration may directly affect current transfer and electrical output stability [1], [7].

2.2 Maintenance Concept and Reliability-Centered Maintenance Perspective

Aircraft maintenance is fundamentally intended to preserve airworthiness, functional integrity, and operational reliability throughout the service life of the aircraft and its components. In engineering practice, maintenance actions may be preventive, scheduled before failure occurs, or corrective, performed after a fault or failure has already taken place. The central challenge in maintenance planning is therefore not only how to repair a failed component, but how to determine an interval or task strategy that minimizes operational risk while maintaining technical and economic efficiency [3], [11].

From the perspective of Reliability-Centered Maintenance (RCM), an effective maintenance program should be based on actual failure behavior rather than on fixed intervals alone. This means that maintenance tasks need to be evaluated according to how components fail, how often they fail, and what operational consequences are produced by those failures. Under this logic, a scheduled task remains appropriate only if it is technically justified by the observed degradation pattern and contributes meaningfully to failure prevention. This theoretical view is especially relevant when a component experiences repeated unscheduled removals before reaching its scheduled maintenance threshold [3], [12].

2.3 Reliability as a Basis for Maintenance Decision-Making

Reliability is generally defined as the probability that a component or system performs its required function under stated operating conditions for a specified period of time [9], [13]. In the context of aircraft maintenance, reliability analysis is important because it provides a structured way to evaluate whether component behavior in service remains consistent with maintenance expectations. Rather than relying only on nominal maintenance intervals, reliability analysis allows maintenance decisions to be supported by measurable operational evidence.

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For removal-driven aircraft components, reliability assessment is particularly useful because failure does not only represent a technical defect, but also an operational event with consequences such as delay, aircraft-on-ground condition, or unplanned maintenance burden. Therefore, reliability is not merely a statistical concept in this paper, it is also a practical engineering basis for reassessing whether the current maintenance interval remains appropriate for the component under actual service conditions [13], [14].

2.4 Time Since Installation and Mean Time To Failure

A central variable in component life analysis is Time Since Installation (TSI), which represents the accumulated operating age of a component since it was installed on the aircraft. In aircraft maintenance practice, TSI is commonly expressed in flight hours, flight cycles, or calendar time, depending on the most relevant exposure measure for the component being studied. For a starter generator, flight hours are an appropriate life measure because the component is continuously exposed to operational duration, electrical load, and rotating mechanical stress during service [1], [15].

Another important concept is Mean Time To Failure (MTTF), which represents the average operating time until failure occurs in a non-repairable or failure-observed context. In engineering terms, MTTF is useful because it provides a summary indication of component durability and can serve as an initial reference for preventive maintenance evaluation. However, MTTF should not be interpreted in isolation. It becomes more meaningful when combined with the broader reliability function and observed failure trend, since two components with similar average life may still have very different failure distributions and maintenance implications [9], [15].

2.5 Distribution-Based Life Analysis in Reliability Engineering

Failure-time data in engineering systems rarely occur in a perfectly uniform pattern. For that reason, reliability engineering commonly uses probability distributions to represent time-to-failure behavior. Distribution-based life analysis helps identify how failure risk evolves as component age increases. In practical terms, this is important because maintenance interval decisions should depend not only on average life, but also on the shape of the failure pattern over time [9], [10].

Several statistical distributions are commonly used in life data analysis, including normal, exponential, Weibull, and lognormal distributions. Each distribution reflects a different failure behavior and may lead to different engineering interpretations. The choice of distribution should therefore be guided by the actual data pattern rather than by assumption alone. In maintenance studies, the selected distribution becomes the basis for estimating characteristic life parameters, survival tendency, and the appropriateness of age-based maintenance actions [10], [15].

In the present study, distribution identification is important because the objective is not only to describe failure events, but also to support maintenance interval reassessment based on the observed operating life of the starter generator. A suitable statistical distribution allows the analyst to estimate how early failures occur relative to the current scheduled interval and whether a shorter interval may be more technically justified.

2.6 Reliability Function and Survival Behavior

The reliability function, usually written as *R(t)*, expresses the probability that a component will continue to perform its intended function beyond a given operating time *(t)*. In maintenance applications, this function is useful because it translates failure data into a survival-based interpretation. Instead of asking only when components fail on average, reliability analysis asks how likely a component is still to survive at a particular age [9], [10].

This survival perspective is highly relevant to scheduled maintenance decisions. If the reliability level declines substantially before the currently assigned maintenance threshold, then the interval may no longer be technically appropriate. In such a case, a shorter preventive interval may reduce the probability of unscheduled removal. Therefore, the reliability function provides a direct theoretical bridge between observed life data and maintenance-interval evaluation.

2.7 Failure Trend and Critical Failure Mode

Besides average life and survival probability, maintenance evaluation also needs to consider the failure trend and the dominant failure mode. A failure trend shows whether the frequency of failures increases, stabilizes, or decreases over the observation period. In engineering interpretation, an increasing trend may suggest worsening degradation exposure, ineffective preventive maintenance timing, or the growing influence of age-related wear [13], [14].

The identification of the dominant failure mode is equally important. If most failures are concentrated in one specific subcomponent or degradation mechanism, maintenance action can be focused more effectively on that critical area. In the context of starter generators, brush wear is especially significant because brushes are directly involved in electrical transfer and are subject to progressive physical wear during service. Therefore, when brush deterioration becomes the most frequent removal cause, it provides a strong technical basis for reviewing the interval of brush-related maintenance tasks [6], [7].

2.8 Component Removal Rate and Mean Time Between Unscheduled Removal

For removal-driven components, maintenance performance can also be interpreted through quantitative indicators that reflect unscheduled removal behavior. Two useful indicators in this context are Component Removal Rate (CRR) and Mean Time Between Unscheduled Removal (MTBUR). These indicators help translate operational removal data into performance measures that are easier to interpret from a maintenance-planning perspective.

The CRR represents the frequency of unscheduled removals relative to operational exposure. In the paper, this metric is defined as the number of unscheduled removals multiplied by 1000 and divided by the product of total flight hours and the quantity of the component installed per aircraft. The equation, rewritten in a cleaner journal format while preserving the original meaning, is as follows:

$$CRR = \frac{Number\ of\ Unscheduled\ Removals \times 1000}{Total\ Flight\ Hours \times Quantity\ per\ Aircraft} \quad (1)$$

The MTBUR represents the average operational exposure between one unscheduled removal event and the next. In the

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thesis, this indicator is expressed as total flight hours multiplied by the quantity per aircraft, divided by the number of unscheduled removals. The corrected and journal-ready notation is:

$$MTBUR = \frac{Total\ Flight\ Hours \times Quantity\ per\ Aircraft}{Number\ of\ Unscheduled\ Removals} \quad (2)$$

These two indicators are useful because they connect reliability observation with maintenance significance. A higher CRR indicates more frequent unscheduled component removal relative to exposure, while a higher MTBUR indicates better spacing between unscheduled removal events. In this paper, both metrics support the interpretation of whether the existing maintenance interval remains acceptable from an operational reliability standpoint.

2.9 Maintenance Interval Reassessment as an Engineering Decision

A scheduled maintenance interval should not be treated as permanently optimal without operational verification. In reliability-based maintenance practice, interval reassessment becomes necessary when operational evidence shows repeated failure before the intended preventive threshold. This reassessment does not automatically replace the original maintenance program; rather, it provides an engineering basis to evaluate whether the current interval still performs its preventive function effectively [3], [4].

Accordingly, the theoretical basis of this study lies in linking practical removal data with reliability analysis to support maintenance decision-making. The key logic is that if the observed component life, survival behavior, dominant failure mode, and unscheduled removal indicators consistently indicate premature degradation relative to the existing scheduled limit, then a shorter maintenance interval may be justified as a preventive strategy. This forms the conceptual foundation for the methodology and analysis presented in the next sections.

3. RESEARCH METHODOLOGY

3.1 Research Design

This paper employed a quantitative case-study approach to evaluate the maintenance behavior of starter generator part number 8260-124 installed on ATR72-212A aircraft. The case-study design was selected because the research focused on a specific component, a specific aircraft type, and a specific operational context, with the objective of linking actual maintenance records to reliability-based maintenance decision-making. In this study, the component was assessed not only from the perspective of technical failure occurrence, but also from the standpoint of maintenance interval suitability and operational consequence.

The study was conducted using historical maintenance data from an airline operator identified in this paper as Airline X. The observation covered the period from 2019 to 2024 and focused on both scheduled and unscheduled starter generator removals. The methodological logic of the study was to identify the dominant failure mode, evaluate the life behavior of the removed units, estimate the component reliability characteristics, and then examine whether the existing maintenance interval remained technically appropriate.

3.2 Object of Study and Research Scope

The object of this study was the DC starter generator with part number 8260-124 used on ATR72-212A aircraft. The research scope was limited to maintenance events associated with this component, particularly those related to unscheduled removals and reliability-related performance indicators. The study did not evaluate the entire aircraft electrical system; instead, it concentrated on the starter generator as the specific removal-driven component under investigation.

The scope of the study was also limited to failure behavior observed in operational service and to maintenance tasks associated with the existing maintenance program, especially the brush bearing change interval. The main analytical interest was whether the existing scheduled maintenance threshold was still appropriate when compared with actual field removal behavior.

3.3 Data Sources

The study used both primary and supporting technical data. The primary operational data consisted of:

- Aircraft Flight Maintenance Log (AFML) data, used to identify starter generator removals and component operating age at removal; and
- Technical Delay Report data, used to identify operational disturbances associated with starter generator-related technical events.

The supporting technical references consisted of the Component Maintenance Manual (CMM), Aircraft Maintenance Manual (AMM), and the operator’s Maintenance Program. These documents were used to interpret the function of the component, understand relevant maintenance tasks, confirm the scheduled maintenance interval, and support technical evaluation of the observed failure and removal behavior [1], [2].

3.4 Data Preparation and Classification

The collected maintenance data were first organized chronologically to distinguish between scheduled removals and unscheduled removals. The thesis records show a total of 65 removal events during the observation period, consisting of 39 scheduled removals and 26 unscheduled removals. The unscheduled removal dataset was then used as the core basis for failure classification and reliability analysis.

Each unscheduled removal record was classified according to its stated removal reason. These reasons were then grouped into broader failure categories, including brush worn out, engine cannot start, bearing wear, and DC generator fault. The purpose of this classification step was to identify the dominant failure mode and determine whether the removal pattern was concentrated in a specific maintenance-sensitive subcomponent.

3.5 Identification of the Dominant Failure Mode

To identify the critical failure mode, the grouped unscheduled removal data were analyzed using frequency comparison and Pareto logic. This step was intended to determine which failure category contributed the largest share of unscheduled removals and therefore should receive the main attention in the maintenance interval evaluation. The use of Pareto-based interpretation is appropriate in this context because it highlights the most operationally significant source of removal events rather than treating all failure categories as equally important.

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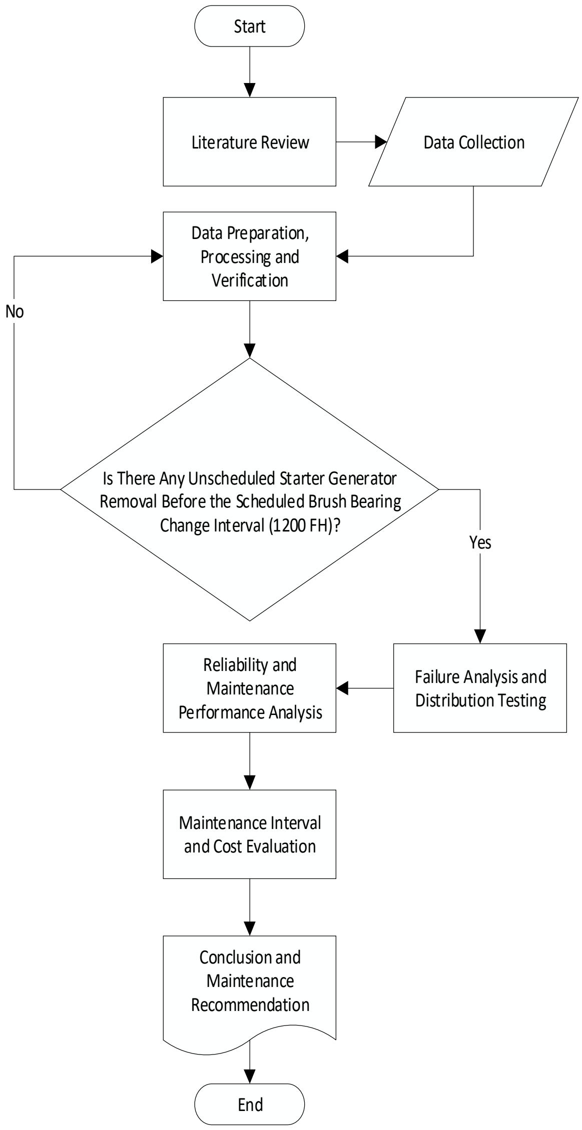

Figure 3: Research flowchart

Table 1: Removal Summary of Starter Generator 8260-124 (2019–2024)

Year	Scheduled	Unscheduled	Total
2019	5	2	7
2020	9	4	13
2021	5	6	11
2022	5	8	13
2023	10	2	12
2024	5	4	9
Total	39	26	65

The resulting classification showed that brush worn out was the most dominant unscheduled removal reason. This finding was then carried forward into the reliability interpretation stage, since the dominant failure mode becomes the most relevant maintenance driver for interval reassessment.

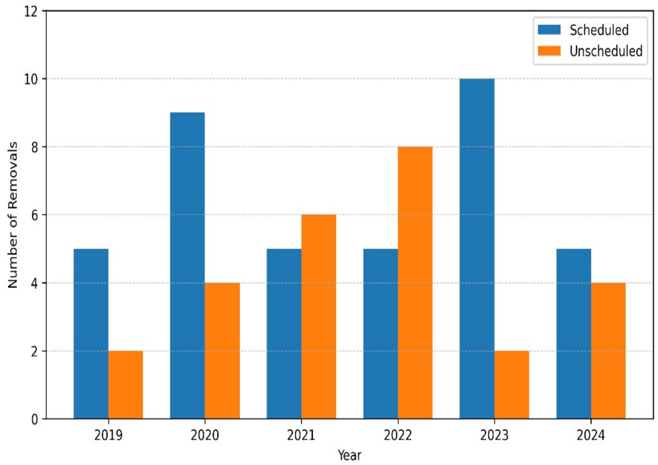

Figure 4: Starter generator removal pattern, 2019-2024

3.6 Reliability Data Construction Using TSI

The main life variable used in this study was TSI, expressed in flight hours. For each unscheduled removal event, the TSI value represented the operating age of the removed starter generator unit at the time of removal. These TSI values formed the life dataset used for reliability analysis and statistical distribution identification. Because the component is exposed continuously during aircraft operation, flight hours were considered the most relevant age measure for this study [10], [15].

The TSI dataset derived from the unscheduled removal records was then used to estimate the life behavior of the component relative to the existing scheduled maintenance interval. In practical terms, this step was essential because the study aimed to determine whether unscheduled failures were occurring significantly before the scheduled threshold of 1200 flight hours. The data of unscheduled removal records of DC starter generator 8260-124 depicted in Table 2.

3.7 Distribution Identification and MTTF Estimation

The statistical analysis was conducted using Minitab, following the distribution-identification procedure described in the thesis. The TSI data were tested against several candidate distributions, namely Weibull, lognormal, exponential, and normal. The most suitable distribution was selected based on the highest correlation coefficient and the lowest Anderson–Darling value, consistent with the applied reliability-analysis procedure [10], [15].

After distribution identification, the study estimated the MTTF and examined the associated survival behavior of the starter generator. The purpose of this step was not only to determine the average life of the removed units, but also to evaluate the probability of survival at selected operating ages relative to the currently applied maintenance interval. This provided the analytical basis for judging whether the preventive threshold should remain unchanged or be reduced.

3.8 Operational Reliability Indicators

In addition to life-distribution analysis, the study also used removal-based performance indicators to interpret maintenance effectiveness. The first indicator was CRR, which expresses the frequency of unscheduled removals relative to operational exposure. The second indicator was

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Table 2: Unscheduled removal records of DC starter generator 8260-124

Date	Serial Number	Position	TSI	Reason for Removal
24-Jul-2024	5655	ENG 2	989	D/T starter ENG 2 no NH
14-May-2024	5645	ENG 2	896	Brush worn out
27-Apr-2024	5688	ENG 1	886	D/T start ENG 1 fault
25-Jan-2024	6106	ENG 2	1084	Brush worn out
21-Oct-2023	5707	ENG 1	845	DC generator 1 fault
6-Aug-2023	6062	ENG 1	951	Brush worn out
29-Jul-2022	5707	ENG 2	950	D/T bearing wear
9-May-2022	5538	ENG 2	885	Brush worn out
29-Apr-2022	5645	ENG 1	1018	Brush worn out
7-Apr-2022	5746	ENG 1	984	Brush worn out
13-Mar-2022	5534	ENG 1	932	Brush worn out
10-Mar-2022	5745	ENG 1	1012	Brush worn out
26-Jan-2022	5776	ENG 1	806	Brush worn out
7-Jan-2022	5688	ENG 2	812	D/T start ENG 2 fault
19-Nov-2021	5655	ENG 1	821	Brush worn out
18-Nov-2021	5782	ENG 2	965	D/T fault
10-Oct-2021	5782	ENG 2	897	Brush worn out
7-Sep-2021	5649	ENG 1	827	D/T ENG start fault
27-May-2021	5741	ENG 1	852	D/T bearing wear
6-Apr-2021	5739	ENG 2	865	D/T bearing wear
19-Nov-2020	5645	ENG 2	998	Brush worn out
10-Sep-2020	5637	ENG 1	865	D/T NH cannot raise
20-Aug-2020	5746	ENG 2	768	ENG 2 cannot start
13-Mar-2020	5637	ENG 1	877	Brush worn out
23-Nov-2019	5617	ENG 1	967	D/T bearing wear
23-Apr-2019	5688	ENG 1	821	Brush worn out

Note: D/T = defect/trouble indication; NH = high-pressure spool rotational speed.

MTBUR, which reflects the average exposure interval between unscheduled removal events. These indicators were calculated using the formulas already established in the theoretical framework and were used to strengthen the interpretation of maintenance performance over time.

The operational significance of these indicators lies in their ability to complement MTTF-based analysis. While MTTF describes average life behavior at the unit level, CRR and MTBUR provide fleet-oriented insight into how often unscheduled removal events occur in service. Together, these metrics offer a more complete basis for maintenance interval reassessment.

Table 3: Failure Category Recapitulation of DC Starter Generator 8260-124

Failure Mode	Number of Failures	Cumulative Number of Failures	Failure Percentage (%)	Cumulative Percentage (%)
Brush Worn Out	14	14	53.8	53.8
Engine Cannot Start	7	21	26.9	80.7
Bearing Wear	4	25	15.4	96.1
DC Generator Fault	1	26	3.9	100.0

3.9 Maintenance Interval Evaluation

Once the dominant failure mode, TSI distribution, MTTF, survival behavior, and removal indicators had been identified, the study proceeded to the maintenance-interval evaluation stage. This stage compared the observed life behavior of the component with the existing scheduled maintenance threshold in the operator's maintenance program. The principal question was whether the current 1200 flight-hour brush bearing change interval still functioned effectively as a preventive maintenance boundary.

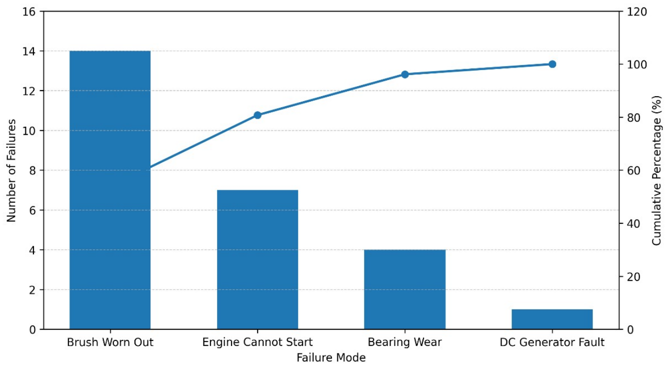

Figure 5: Pareto Diagram of Starter Generator Failure Frequency

The evaluation was then used to formulate alternative maintenance interval options. In the thesis, the analysis considered shorter intervals, particularly 1000 flight hours and 800 flight hours, as candidate preventive strategies. These alternatives were assessed in relation to the observed failure life, the proportion of units failing before 1200 flight hours, and the expected reduction of unscheduled removal risk. The final recommendation was therefore developed as a reliability-informed maintenance decision rather than as a purely descriptive statistical result.

3.10 Research Workflow

The methodological sequence of the study followed the workflow (Figure 3). This workflow was designed to ensure that the final maintenance recommendation emerged from a structured progression beginning with raw maintenance records and ending with reliability-based engineering interpretation.

4. RESULTS AND DISCUSSION

4.1 Removal Pattern of Starter Generator 8260-124

The maintenance records show that the starter generator part number 8260-124 experienced both scheduled and unscheduled removals during the observation period from 2019 to 2024. In total, 65 removal events were recorded, consisting of 39 scheduled removals and 26 unscheduled removals. This result indicates that although the component was being maintained under an established maintenance program, a substantial portion of removals still occurred outside the intended preventive schedule. From an operational maintenance perspective, this is an important signal that the scheduled interval may not have fully captured the actual in-service degradation behavior of the component. Table 1 presents the yearly distribution of scheduled and unscheduled

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events over the 2019–2024 period. A total of 65 events were recorded, consisting of 39 scheduled events and 26 unscheduled events.

The annual pattern also shows that unscheduled removals were not isolated events. Instead, they appeared repeatedly across multiple years, with particularly notable counts in 2021 and 2022. This repeated occurrence suggests that the problem was not limited to a one-time anomaly or a single defective unit, but reflected a recurring maintenance issue associated with the operational life of the component. Such a pattern supports the need for reliability-based analysis rather than relying only on nominal maintenance scheduling. Yearly distribution of scheduled and unscheduled starter generator removals during the 2019-2024 periods is shown in Figure 4.

4.2 Unscheduled Removal Characteristics

The unscheduled removal dataset forms the core basis of the failure analysis. The thesis records list 26 unscheduled removals, each accompanied by TSI, serial number, engine position, and stated removal reason. These data are important because they provide the component-level operational life record required for reliability analysis. The TSI values show that many units were removed well before the scheduled brush bearing change threshold of 1200 flight hours, indicating that early removal before the preventive limit was a recurring condition rather than an exceptional one. Table 2 summarizes the unscheduled removal records of the DC starter generator 8260-124 during the observation period. The table includes the removal date, serial number, engine position, TSI, and the reported reason for removal.

A practical implication of this result is that the current maintenance threshold did not prevent a considerable number of in-service removals. In reliability terms, this means that the preventive boundary was likely positioned too late for a significant portion of the population. Therefore, the observed removal ages already provide an initial indication that the current interval should be reassessed against actual operational performance rather than maintained solely on program convention.

4.3 Dominant Failure Mode

After the unscheduled removal records were grouped by removal reason, the failure classification showed that brush worn out was the dominant failure category. It accounted for 14 of the 26 unscheduled removals, corresponding to 53.8% of the total. The remaining cases were distributed among engine cannot start (26.9%), bearing wear (15.4%), and DC generator fault (3.9%) as shown Table 3. This result clearly indicates that the reliability problem was concentrated primarily in one wear-related subcomponent mechanism rather than being distributed evenly across multiple unrelated failure types.

The Pareto interpretation strengthens this conclusion by showing that brush wear alone contributed more than half of all unscheduled removals as shown Figure 5 From a maintenance-engineering standpoint, this is highly significant because it means that interval reassessment can be focused primarily on brush-related deterioration rather than on the component as a whole in a generic sense. This finding is also consistent with previous studies that identified brush-related degradation as one of the main drivers of starter-generator reliability loss [6], [7].

4.4 Scheduled Maintenance Context

The operator's maintenance program specified two relevant tasks for the starter generator: removal for restoration at 3600 flight hours and removal for bearing and brush discard at 1200 flight hours. Within the context of this study, the 1200 flight-hour brush bearing change interval is the most important preventive maintenance threshold, because the majority of unscheduled removals were associated with brush-related deterioration. Therefore, the comparison between observed TSI and this scheduled interval becomes the central basis for maintenance interval reassessment.

As shown Table 4, summarizes the maintenance program applied to the DC starter generator 8260-124, including the task reference, task description, threshold interval, and the applicable job procedures. The scheduled removal records further show that preventive removals were indeed being performed under the existing maintenance program. However, because unscheduled removals still occurred repeatedly before the preventive threshold, the maintenance program cannot be judged solely by its existence; it must be judged by its effectiveness in preventing premature in-service removals. This is precisely where reliability analysis becomes necessary.

Table 4: Maintenance Program for DC Starter Generator 8260-124

Task	Description	Threshold Interval	Job Procedure
243261-RAI-10000-2	Removal of the starter/generator for restoration	I: 3600 FH	CMM: 243265; MP: ATR-A-24-32-60-00ZZZ-520Z-A; MP: ATR-A-24-32-60-00ZZZ-720Z-A
243261-RAI-11000-2	Removal of the starter/generator for bearing and brushes discard	I: 1200 FH	CMM: 243265; MP: ATR-A-24-32-60-00ZZZ-520Z-A; MP: ATR-A-24-32-60-00ZZZ-720Z-A

Table 5: Scheduled removal of DC starter generator 8260-124

Serial Number (S/N)	Position	TSI	Date	Scheduled Reason
5878	ENG 2	1104	28-Dec-2024	Hardtime BBC
6101	ENG 1	1141	11-Sep-2024	Hardtime BBC
5894	ENG 2	1100	9-Sep-2024	Hardtime BBC
5856	ENG 2	1182	28-Aug-2024	Hardtime BBC
5878	ENG 2	1132	24-May-2024	Hardtime BBC
6101	ENG 2	1372	15-Sep-2023	Hardtime BBC
5789	ENG 1	1278	12-Aug-2023	Hardtime BBC
5655	ENG 1	1153	12-Jun-2023	Hardtime BBC
5643	ENG 2	1308	12-Jun-2023	Hardtime BBC
5894	ENG 1	771	13-May-2023	Hardtime BBC
5555	ENG 2	1173	12-May-2023	Hardtime BBC
5688	ENG 2	1205	5-Apr-2023	Hardtime BBC
5745	ENG 1	882	16-Mar-2023	Hardtime BBC
5617	ENG 2	754	3-Feb-2023	Hardtime BBC
5534	ENG 2	1142	24-Jan-2023	Hardtime BBC
5553	ENG 2	1282	13-Aug-2022	For restoration
5789	ENG 2	1249	9-Jul-2022	Hardtime BBC
5555	ENG 2	1322	13-Mar-2022	Hardtime BBC
5894	ENG 1	1093	17-Feb-2022	Hardtime BBC

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Serial Number (S/N)	Position	TSI	Date	Scheduled Reason
5643	ENG 1	563	11-Jan-2022	D/T stagger removal
5746	ENG 1	1244	14-Nov-2021	Hardtime BBC
5707	ENG 2	1290	11-Oct-2021	Hardtime BBC
5553	ENG 2	1212	3-Sep-2021	Hardtime BBC
5534	ENG 2	1200	25-May-2021	For restoration
5776	ENG 1	1151	10-Feb-2021	Hardtime BBC
5745	ENG 1	1188	22-Dec-2020	Hardtime BBC
5739	ENG 1	1153	16-Oct-2020	Hardtime BBC
5649	ENG 2	1223	25-Sep-2020	Hardtime BBC
5643	ENG 2	1199	12-Jun-2020	For restoration
5894	ENG 2	1081	4-Mar-2020	Hardtime BBC
5789	ENG 1	1178	4-Mar-2020	Hardtime BBC
5538	ENG 2	1007	24-Feb-2020	Hardtime BBC
5878	ENG 2	1106	21-Feb-2020	Hardtime BBC
5856	ENG 1	1100	20-Feb-2020	Hardtime BBC
5553	ENG 1	1228	14-Dec-2019	Hardtime BBC
5745	ENG 2	1341	24-Sep-2019	Hardtime BBC
5739	ENG 1	1341	24-Sep-2019	For restoration
5617	ENG 1	1344	22-Sep-2019	Hardtime BBC
5782	ENG 2	1293	12-Sep-2019	Hardtime BBC

As shown Table 5 present the scheduled removal records of the DC starter generator 8260-124. The table includes the serial number, engine position, TSI, removal date, and the stated scheduled reason for removal.

4.5 Distribution Identification and Reliability Model Selection

The TSI dataset of unscheduled removals was tested against several candidate distributions using Minitab. The comparison included Weibull, lognormal, exponential, and normal distributions. Based on the statistical criteria reported in the thesis, the lognormal distribution was selected as the most appropriate model because it produced the highest correlation coefficient (0.989) and the lowest Anderson–Darling value (0.746) among the tested candidates. This result indicates that the life behavior of the starter generator removals in this dataset was represented more adequately by a lognormal pattern than by the other tested distributions.

Table 6 presents the goodness-of-fit test results for the TSI data under several candidate distributions. Among the evaluated models, the lognormal distribution showed the lowest adjusted Anderson–Darling value and the highest correlation coefficient, indicating the best overall fit to the observed TSI data. From an engineering perspective, the selection of lognormal distribution implies that the failure process was influenced by progressive degradation rather than by purely random failure occurrence. Although the study did not extend into a deeper mechanistic material model, the dominance of brush wear and the repeated removals before 1200 flight hours make this result technically plausible. The statistical fit therefore supports the interpretation that the observed removals reflected a real degradation-life pattern rather than incidental event variation.

Table 6: Distribution test results for starter generator TSI data

Distribution	Anderson–Darling (Adjusted)	Correlation Coefficient
Weibull	1.450	0.960
Lognormal	0.746	0.989
Exponential	20.327	*
Normal	0.787	0.987

Note: The symbol (*) indicates that the correlation coefficient was not reported for the exponential distribution.

Table 7: Estimated Mean Time To Failure (MTTF)

Characteristic	Estimate
Mean (MTTF)	907.022
Standard Error	16.1409
95% Lower Confidence Interval	875.932
95% Upper Confidence Interval	939.216

4.6 Mean Time To Failure and Survival Interpretation

Using the selected distribution, as shown Table 7 the study estimated the MTTF of the starter generator at 907.022 flight hours, with a 95% confidence interval of approximately 875.9 to 939.2 flight hours. This result is particularly important because it is substantially lower than the currently applied 1200 flight-hour preventive threshold. In practical terms, the average removal life of the failed population was already below the existing brush bearing change interval, which means that the preventive limit was not sufficiently conservative for the observed operational condition. Table 7 presents the estimated MTTF of the DC starter generator.

Table 8: Survival function of starter generator TSI data

Survival Probability (%)	TSI
98.6	740
97.2	760
94.8	780
91.1	800
85.8	820
78.9	840
70.6	860
61.4	880
51.6	900
41.9	920
33.1	940
25.1	960
18.4	980
13.1	1000
8.9	1020
5.9	1040
3.9	1060
2.4	1080
1.5	1100
0.9	1120

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The survival interpretation reinforces this conclusion. According to the thesis, the survival function indicated that only 51.6% of units were expected to survive to 900 flight hours, and only 41.9% were expected to survive to 920 flight hours. These values show that the survival probability had already declined markedly well before the current 1200 flight-hour threshold. Therefore, from a preventive maintenance perspective, retaining the current interval means accepting a high risk that a substantial fraction of the population will fail before reaching the scheduled removal age. Table.8 presents the survival function of the DC starter generator as a function of TSI. The results show a progressive decline in survival probability as TSI increases, indicating an increasing likelihood of failure with longer operating time.

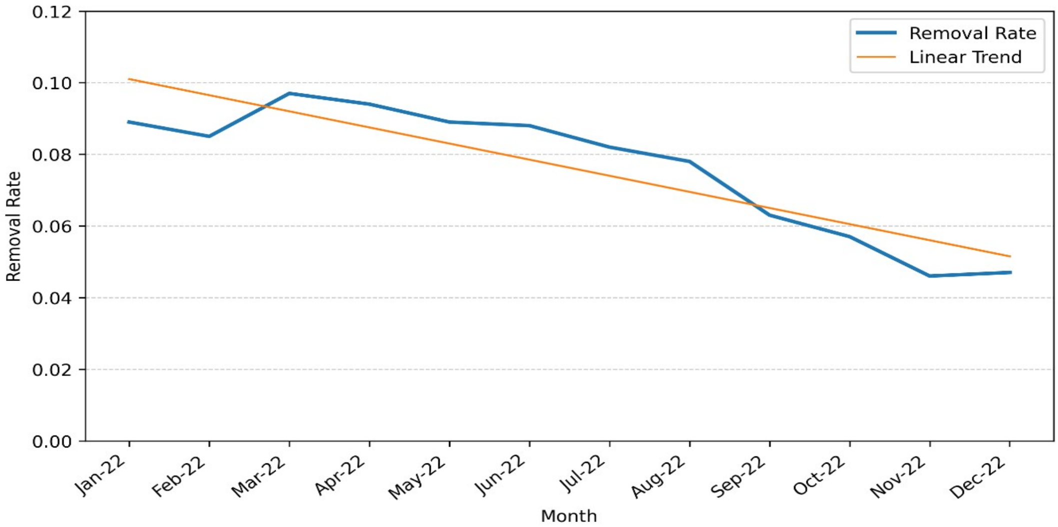

Figure 6: Starter Generator Removal Rate Trend, 2022

The survival probability remained above 50% up to approximately TSI = 900, after which it declined more sharply, reaching below 10% at TSI = 1020.

4.7 Operational Reliability Trend

This paper also examined the removal-rate trend over time. The results showed that the CRR trend was not stable across the observation window. The trend in 2022 appeared to decline, but in 2023 it increased again during the middle to later part of the year, and in 2024 it continued to show an increasing tendency. This result is important because it indicates that the problem was not self-correcting under the existing maintenance program. Instead, the frequency of unscheduled removals remained operationally relevant and even showed signs of worsening in later periods. Monthly trend of the rolling 12-month starter generator removal rate during 2022 is shown in Figure 6.

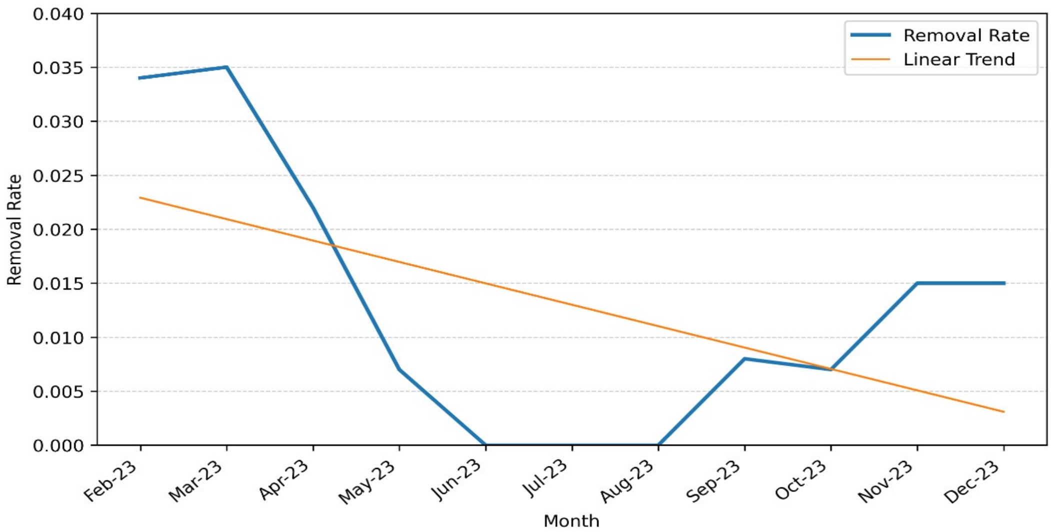

Figure 7: Starter Generator Removal Rate Trend, 2023

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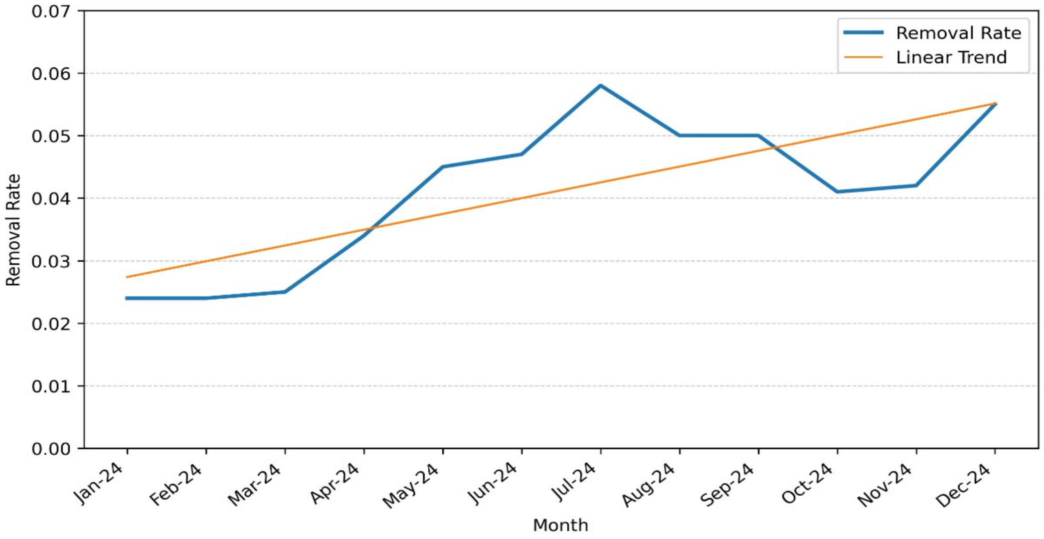

Figure 8: Starter Generator Removal Rate Trend, 2024

Monthly trend of the rolling 12-month starter generator removal rate during 2023 is shown in Figure 7. Monthly trend of the rolling 12-month starter generator removal rate during 2024 is shown in Figure 8. From the standpoint of maintenance significance, an increasing removal trend supports the argument that the current interval should not simply be retained without review. When the dominant failure mode is wear-related and the removal frequency remains operationally disruptive, interval reassessment becomes an engineering response grounded in both statistical evidence and operational need.

4.8 Maintenance Interval Reassessment

The core practical finding of this study is that the existing 1200 flight-hour brush bearing change interval appears too long relative to the actual removal behavior observed in service. Since the estimated MTTF is approximately 907 flight hours and the survival probability has already declined substantially before 1000 flight hours, a shorter preventive threshold becomes technically reasonable. Based on the thesis analysis, the two main candidate alternatives were 1000 flight hours and 800 flight hours.

This study presented interval-scenario illustrations comparing the current schedule with shorter alternatives. The 1000-flight-hour option would reduce exposure to premature failure relative to the existing program while still preserving a moderate preventive interval. The 800-flight-hour option is more conservative and offers a higher preventive margin against unscheduled removal, particularly for brush-related wear. In reliability terms, the shorter interval is justified not because every unit fails early, but because the observed population behavior shows that too many units fail before reaching 1200 flight hours.

Figure 9 shows schematic representation of the scheduled starter generator removal program at 1200 FH, 2400 FH, and 3600 FH, including the associated maintenance costs. Figure.10 shows schematic representation of starter generator removal option 1, including the maintenance actions, associated costs, and cost per flight hour. Figure.11 shows schematic representation of starter generator removal option 2, including the maintenance actions, associated costs, and cost per flight hour.

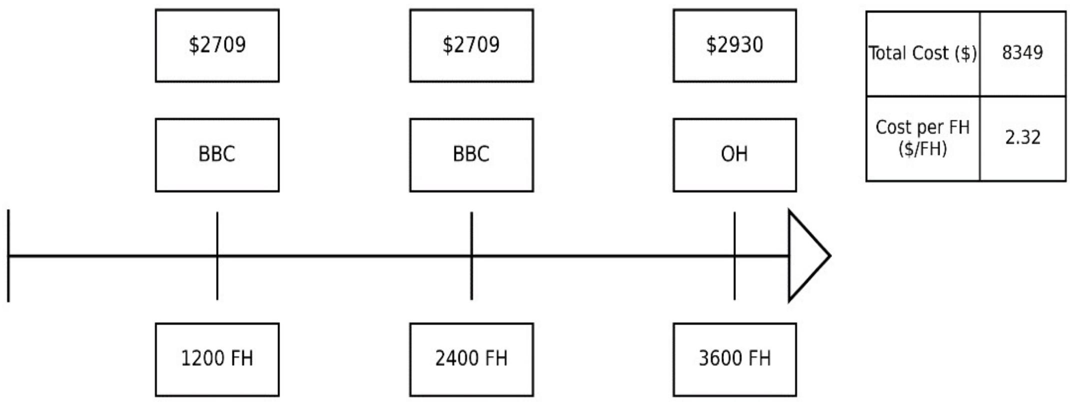

Figure 9: Scheduled removal scheme under current interval

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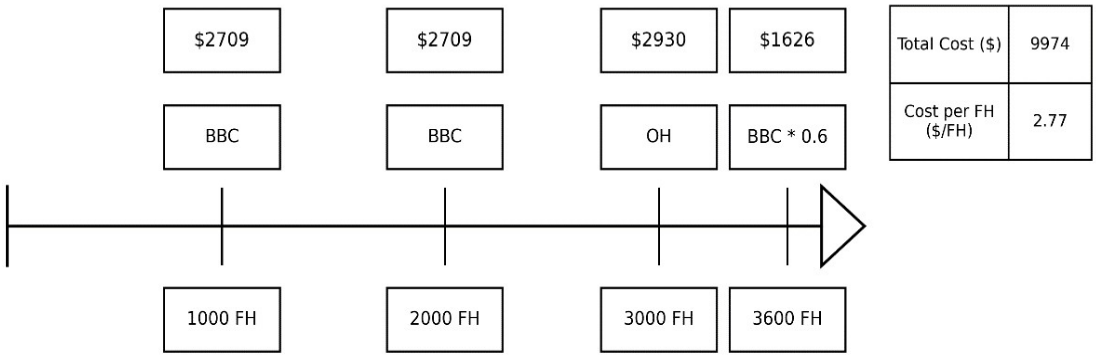

Figure 10: Alternative Maintenance Interval Option 1

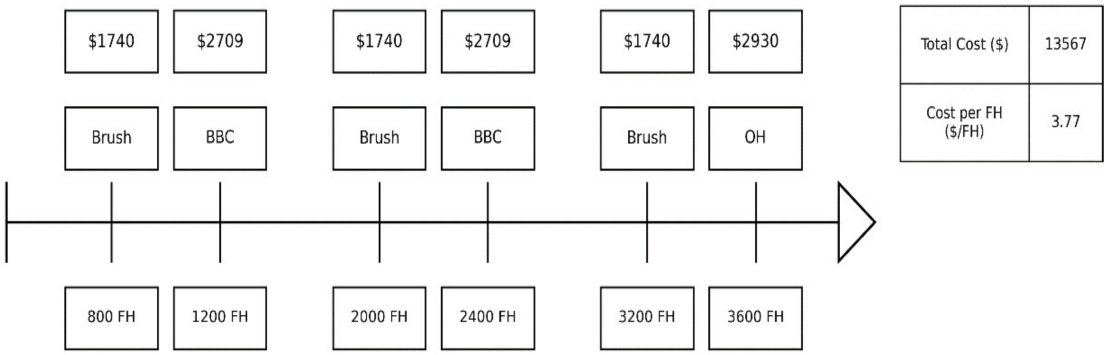

Figure 11: Alternative maintenance interval option 2

4.9 Engineering Interpretation of the Recommended Option

The thesis concludes that the more conservative interval option, corresponding to the 800 flight-hour strategy, is operationally more effective in reducing disruption risk. The reason is not only statistical but also practical: a shorter interval provides a greater preventive margin against brush-related deterioration before it develops into an unscheduled operational event. In an airline environment where unscheduled removals may produce delay, return to apron, or aircraft-on-ground consequences, such a preventive margin can be more valuable than merely maximizing nominal component life.

At the same time, this recommendation should be interpreted as a reliability-informed maintenance adjustment rather than as an automatic replacement of the original maintenance program. The result provides engineering evidence that the current threshold may be too late under the observed service condition, and that a shorter interval would likely reduce unscheduled removal exposure. In this sense, the study demonstrates how actual maintenance records, statistical life analysis, and maintenance performance indicators can be combined into a practical decision-support basis for interval reassessment.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study has shown that the maintenance behavior of starter generator part number 8260-124 on ATR72-212A aircraft is strongly influenced by a dominant wear-related failure mechanism, namely brush worn out. Based on the unscheduled removal records analyzed during the 2019–2024 observation period, brush wear was accounted for 53.8% of all unscheduled removal events. Hence, it makes the most critical failure mode in the observed population. This indicates that the reliability problem of the component is not broadly distributed across all internal elements, but is concentrated in one maintenance-sensitive degradation mechanism that is directly relevant to interval reassessment.

The reliability analysis further demonstrated that the current preventive threshold of 1200 flight hours was not fully consistent with the observed field behavior of the component. The selected statistical model identified the starter generator life pattern as best represented by a lognormal distribution, with an estimated MTTF of 907.022 flight hours, which is substantially lower than the currently applied brush bearing change interval. In addition, the survival function showed that the probability of component survival had already declined considerably before reaching the existing scheduled threshold. These results confirm that a significant portion of the population was exposed to unscheduled removal risk before the scheduled preventive action was due.

The operational reliability trend also supported this conclusion. Although the removal rate trend was not uniform across all years, the observed increase in later periods indicated that the issue remained operationally significant under the existing maintenance program. Combined with the repeated occurrence of premature removals, this trend strengthens the argument that the current interval should not be maintained without review. From an engineering standpoint, the findings show that actual component life behavior in service must be considered more explicitly in maintenance-interval decision-making.

Accordingly, this study concludes that the current 1200 flight-hour brush bearing change interval is too long relative to the observed reliability behavior of the component. The interval reassessment performed in the thesis indicates that shorter preventive strategies are more technically appropriate. Among the proposed alternatives, the 800 flight-hour option provides the strongest preventive margin against brush-related deterioration and offers the most effective protection against unscheduled removal risk. Therefore, the study demonstrates that reliability-based evaluation of real maintenance records can provide a practical engineering basis for improving scheduled maintenance policy for starter-generator components in ATR72-212A operations.

5.2 Recommendations

Based on the findings of this study, the first recommendation is that the operator should consider adopting a shorter preventive maintenance interval for brush-related starter generator maintenance, with 800 flight hours as the preferred option for operational risk reduction. This recommendation is justified by the fact that the observed failure behavior consistently occurred below the current 1200 flight-hour threshold, and the shorter interval provides a more conservative and operationally safer preventive boundary.

The second recommendation is that maintenance planning should place greater emphasis on the monitoring and control of brush-related deterioration, since this failure mode dominates the unscheduled removal population. In practical terms, this means that maintenance attention, spare provisioning, and inspection emphasis should be focused on the brush subsystem as the critical maintenance driver of the starter generator in the observed fleet condition.

The third recommendation is that the operator should treat the proposed interval adjustment as a reliability-informed maintenance improvement, supported by periodic review of updated maintenance records. If additional operational data become available, the TSI distribution, removal trend, and maintenance performance indicators should be re-evaluated to confirm whether the recommended interval remains appropriate over time. Such a step is important because maintenance optimization should remain responsive to actual field behavior rather than fixed indefinitely without verification [3], [4].

Finally, future research may extend this study by incorporating broader economic modeling, more detailed cost comparison between interval options, or additional condition-monitoring variables related to starter generator degradation. Further studies may also compare failure behavior across different operators or operating environments to determine whether the observed life pattern is operator-specific or more generally representative of this component type in ATR regional turboprop service.

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