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Implementation of Reliability Centered Maintenance (RCM) with Fuzzy Logic in Eliminating Off-Hangar Maintenance on Narrow Body Aircraft

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ABSTRACT

Aircraft maintenance in remote locations is a prevalent challenge for local airlines in Indonesia, leading to diminished productivity and efficiency in the maintenance division. This issue is substantiated by a significant incidence rate of 36% annually, as reported by a national airline. The current solution needed is the improvement of the Maintenance System to eliminate off-hangar maintenance for Narrow Body aircraft in the national aviation service industry. This study aims to identify the causal factors of aircraft requiring maintenance when located outside the primary maintenance facilities and to reduce these occurrences. The Reliability Centered Maintenance (RCM) method is employed to determine the most effective maintenance approach based on system and equipment reliability, and the fuzzy logic method in FMEA is utilized to address ambiguity and uncertainty in risk assessment. Primary data were obtained from Focus Group Discussions (FGD) with experts working in the airline industry. Secondary data were collected from all aircraft experiencing breakdowns outside the main hangar. The findings reveal that the primary factor for maintenance outside the main facilities is the current maintenance policy of Finding Failure (FF), which leads to unpredictable maintenance activities, resulting in damage outside the main facility areas (Batam, Cengkareng, and Surabaya). Incidents of maintenance outside the main facilities can be eliminated by shifting the policy to Time Directed (TD), enabling the company to reduce costs from an initial IDR 342,681,011,118.60 to IDR 70,370,514,198.60, achieving a cost saving of 79.47%.

Keywords: Aircraft, Maintenance, Airlines, RCM, Fuzzy-FMEA.

Introduction

Air transportation is crucial in facilitating international business relations and trade [1]. The global passenger count peaked in 2019 with 4.5 billion passengers but declined to 1.8 billion in 2020 due to the COVID-19 pandemic [2]. An exponential increase in passenger numbers has the potential to be a contributing factor to flight delays if not adequately anticipated by airlines [3]. Figure 1 illustrates the highest percentage of delays at LA Airlines at 34.99% and the lowest at WA Airlines at 23.99%. The average delay across all

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subsidiary operators under this airline group was 29.02% from January 2022 to June 2023.

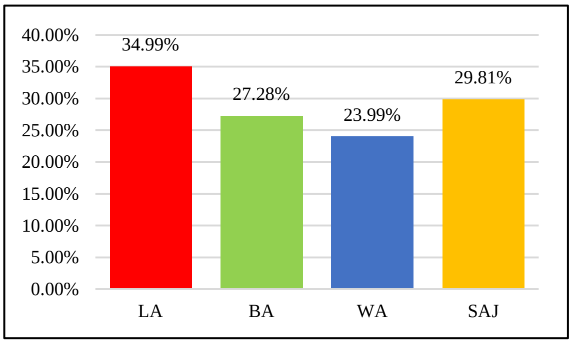

Figure 1. Aircraft Delay Data (Jan 22–Jun 23)

Flight delays can be attributed to many factors within flight operations, such as awaiting pilots, flight crew readiness, aircraft presence, cabin preparation, crew and cabin changeovers, aircraft replacements, fueling delays, and waiting for flight plan documentation [4]. Technical issues have been identified as the primary cause of flight delays globally, contributing to 42% of the total delays 2019 [5].

Aircraft maintenance in remote locations is a common challenge local airlines face in Indonesia, leading to low productivity and performance in maintenance operations. This issue is evident from the high incidence rate of 36% annually, as reported by one of the airline groups. In light of this situation, research is needed to improve the Maintenance System to eliminate off-hangar maintenance for Narrow Body Aircraft in the national aviation service industry.

This study aims to identify the factors causing aircraft maintenance outside the primary maintenance facility and mitigate these occurrences using the Reliability Centered Maintenance (RCM) method and fuzzy logic in FMEA (Fuzzy Failure Mode and Effect Analysis) to address ambiguity and uncertainty in risk assessment.

Reliability Centered Maintenance (RCM) is a methodology based on risk and reliability analysis of machinery or production systems [6]. RCM assists organizations in identifying and prioritizing critical maintenance tasks, reducing downtime, and controlling maintenance and operational costs [7]. Critical steps in the RCM methodology include:

1. Identifying Critical Functions involves evaluating how a system or component functions and impacts overall operations [8].
2. Failure Analysis: This involves using various statistical techniques to understand how and why a system or component fails [9].
3. Evaluating Failure Impact: The consequences of failure regarding operational, safety, and economic impacts are assessed [10].
4. Determining Appropriate Maintenance Actions: Proper maintenance for each asset is based on its operational context and changes over its operational time [11].

Fuzzy Failure Mode and Effect Analysis (Fuzzy FMEA) is a risk analysis approach that integrates Failure Mode and Effect Analysis (FMEA) with fuzzy set theory to address ambiguity and uncertainty in risk assessment related to component and system failures [12]. In this method, fuzzy logic is applied to quantify risk factors, such as severity, occurrence, and detection, which often involve subjective judgment [13].

Maintenance encompasses all activities, including managerial, administrative, and technical actions, throughout the life cycle of an item to maintain or restore it to a state in which it can perform its required function [14].

Methods

This research is categorized as a mixed-method study with a Sequential Exploratory design, beginning with collecting and analyzing quantitative data in the form of secondary data acquisition related to maintenance activities and events involving Aircraft on Ground (AOG) status. This is followed by collecting and analyzing qualitative data through risk assessment to understand the researched object.

The collected data serves as a reference in the data analysis and technique stages, where methods such as Reliability Centered Maintenance (RCM) and Fuzzy Failure Mode and Effect Analysis (FMEA) are used to identify potential failures within a system and determine maintenance policies that align with the challenges faced by aviation service providers. The detailed steps of the data processing flow in this research are as follows:

1. *Reliability Centered Maintenance* (RCM)
   The data obtained is processed using the reliability-centered maintenance (RCM) method to determine the most effective maintenance approach based on system reliability and devices. The RCM process can be broken down into the following stages:
   a. Creating a System Breakdown Structure (SBS), breaking down an extensive aircraft system into smaller, hierarchically organized components [15].
   b. Developing a Pareto diagram to facilitate the detection of prioritized and frequently occurring issues in the central aircraft systems for prompt resolution [16].
   c. Identifying functions and failures from the Pareto results using Fuzzy Failure Mode and Effect Analysis (FMEA). FMEA is filled out by a respondent, such as a Line Maintenance (LM) manager who leads and coordinates all operational activities in the maintenance department. Determining the Fuzzy Risk Priority Number (RPN) values to understand the potential level of failure; higher RPN values indicate a higher level of problems [17]. Experts are asked to define the membership functions of linguistic terms, detailed in Tables 1 - 3, using fuzzy triangular numbers to express propositions close to reality [17].
   The fuzzy rules used in linguistics include:
   1) *Remote* (R)

$$\begin{matrix} \frac{(3-x)}{3-0}; & 0 \le x \le 3 \\ 0; & x \ge 3 \end{matrix} \quad (1)$$

   2) *Low* (L)

$$\mu[x] = \begin{cases} 0; x & x \le 2, x \ge 5 \\ \frac{(x-2)}{(3{,}5-2)}; & 2 \le x \le 3{,}5 \\ \frac{(3{,}5-x)}{(5-3{,}5)}; & 3{,}5 \le x \le 5 \end{cases} \quad (2)$$

   3) *Medium* (L)

$$\mu[x] = \begin{cases} 0; x & x \le 4, x \ge 7 \\ \frac{(x-4)}{(5{,}5-4)}; & 4 \le x \le 5{,}5 \\ \frac{(5{,}5-x)}{(7-5{,}5)}; & 5{,}5 \le x \le 7 \end{cases} \quad (3)$$

   4) *High* (H)

$$\mu[x] = \begin{cases} 0; x & x \le 6, x \ge 9 \\ \frac{(x-6)}{(7{,}5-6)}; & 6 \le x \le 7{,}5 \\ \frac{(7{,}5-x)}{(9-7{,}5)}; & 7{,}5 \le x \le 9 \end{cases} \quad (4)$$

Linguistik	Occurrence	Rank
Remote (R)	Very unlikely to happen (>14 months)	1
	6000 - 9999 hours system (8-14 months)	2
Low (L)	3000 - 5999 JAM System (4-8 months)	3
	2001-2999 JAM System (3-4 months)	4
Medium (M)	1000-2000 hours system (42 days - 3 months)	5
	400-999 jam system (17-42 days)	6
High (H)	100-399 system hours (4-17 days)	7
	10 - 99 system hours	8
Very High (VH)	2-10 hours system	9
	< 2 hours system	10

   5) *Very High* (VH)

$$\mu[x] = \begin{cases} 0; & x \le 8 \\ \frac{(x-8)}{(10-8)}; & 8 \le x \le 10 \\ 1; & x \ge 10 \end{cases} \quad (5)$$

Table 1. Occurrence

Table 2. Severity

Linguistik	Keparahan (Severity)	Rank
Remote (R)	Did not cause any consequences.	1
	The system can operate safely, equipment disruption is not significant.	2
Low (L)	The system continued to operate safely, there was little	3
	The system continues to operate safely, there are minor	4
Medium (M)	The system can operate safely, already causing a number of malfunctions.	5
	The system continues to operate safely, causing	6
High (H)	The system remains operating securely, cannot be run	7
	The system is operating, the main functions of the system	8
Very High (VH)	The system failed to operate and did not comply with safety regulations.	9
	The system is not fit to operate because it can result in sudden accidents, not in accordance with safety regulations.	10

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The inference is conducted from the collection and correlation of rules by implementing the product of all outputs in the fuzzy regions using a probabilistic method as illustrated by the following equation:

$$\mu_{sf_{(xi)}} = \left(\left(\mu_{sf_{(xi)}} + \mu_{kf_{(xi)}}\right) - \left(\mu_{sf_{(xi)}} \cdot \mu_{kf_{(xi)}}\right)\right) \quad (6)$$

where,
$\mu_{sf_{(xi)}}$= is the membership value of the fuzzy solution up to member-i,
$\mu_{kf_{(xi)}}$= represents the membership value of the fuzzy consequent of member-i,
The process then progresses to crisp (defuzzification) to produce the final output using the centroid method, as defined by the following equation:

$$z = \frac{\sum_{j=1}^{n} z_j \mu_{(z_j)}}{\sum_{j=1}^{n} \mu_{(z_j)}} \quad (7)$$

Table 3. Detection

Linguistik	Detection	Rank
Remote (R)	The form and cause of failure are almost certain to be detected and the failure rate is almost certain.	1
	The form and cause of failure may be detected and the failure rate is very high	2
Low (L)	The form and cause of failure may be detected as well as a high failure rate	3
	The form and cause of failure may be detected and the failure rate is slightly high	4
Medium (M)	The form and cause of failure may be detected and the failure is moderate	5
	The form and cause of failure may be detectable and the failure rate is low	6
High (H)	The form and cause of failure may be detectable and the failure rate is very low	7
	The form and cause of failure are difficult to detect	8
Very High (VH)	The form and cause of failure are very difficult to detect	9
	Unable to detect failure	10

d. Logic Tree Analysis (LTA)
The LTA stage is implemented to establish priorities for each failure mode (malfunction), as well as to evaluate and review functions to differentiate mode conditions. The classification in LTA is conducted by a respondent, specifically a Line Maintenance (LM) manager, who leads and coordinates all operational activities in the maintenance department.

e. Selection Task
This process is undertaken to determine appropriate actions for each failure mode, utilizing a selection task diagram and responding to the questions it poses. The Selection Task is completed by a Line Maintenance (LM) manager who leads and coordinates all operational activities in maintenance. Time Directed (TD), Condition Directed (CD), and Finding Failure (FF) are three types of maintenance actions resulting from the respondent's answers.

2. Determination of Critical System Components.
In this phase, critical components are identified based on the highest Risk Priority Number (RPN) values obtained from the Fuzzy-FMEA within the RCM methodology.
3. Determination of Time to Repair (TTR) and Time to Failure (TTF).
TTF refers to the duration from the commencement of a system or component's operation to the occurrence of failure or breakdown[18]. Conversely, TTR is the time taken in the repair process or in restoring a component or system to its operational condition after a failure or breakdown [19].
4. Process of Determining the Distribution of Time to Failure (TTF) and Time to Repair (TTR)
The process of identifying the distribution used for obtaining the repair duration from the time of breakdown is performed using the least-square curve fitting method [20]. This approach determines the distribution of an element by selecting the highest index of fit *(r)* value.
a. The median rank of damages is calculated using the equation:

$$F(t_i) = \frac{i - 0{,}3}{n + 0{,}4} \quad (8)$$

where,
i = represents the *i -th* failure time,
n = the total number of failures
b. The Index of Fit is calculated by the equation:

$$r = \frac{n\sum_{i=1}^{n} x_i y_i - (\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i)}{\sqrt{n[\sum_{t=1}^{n} x_i^2 - (\sum_{t=1}^{n} x_i)^2]} \cdot \sqrt{[\sum_{t=1}^{n} y_i^2 - (\sum_{t=1}^{n} y_i)^2]}} \quad (9)$$

The initial distribution for each distribution type is calculated using the following formulas:

a. Normal Distribution

$$x_i = t_i \quad (10)$$

$$y_i = Z_i = \Phi^{-1}[F(t_i)] = \frac{t_i - \mu}{\sigma} \quad (11)$$

where,
t_i = the *i -th* data point,
Z_i = the normal distribution probability table

b. Lognormal Distribution

$$x_i = \ln(t_i) \quad (12)$$

$$y_i = Z_i = \Phi^{-1}[F(t_i)]$$

$$y_i = \Phi^{-1}\left[\left(\frac{1}{s}\right)\ln t_i - \left(\frac{1}{s}\right)\ln t_{med}\right] \quad (13)$$

Z_i = the normal distribution probability table

c. Weibull Distribution

$$x_i = \ln(t_i) \quad (14)$$

$$y_i = \ln\left[\ln\left(\frac{1}{1-F(t_i)}\right)\right] \quad (15)$$

d. Exponential Distribution

$$x_i = t_i \quad (16)$$

$$y_i = \frac{1}{1-F(t_i)} \quad (17)$$

5. Distribution Fit Test

This process is conducted to avoid errors in model selection and ensure the chosen distribution model aligns with the data. The Goodness of Fit test, with its high probability of rejecting non-fitting distributions, is used. After the initial distribution is determined, two opposing hypotheses can be compared as follows:

H_0 : Repair/failure data approximates a particular distribution.

H_1 : Repair/failure data deviates from a particular distribution.

each distribution differs and can be distinguished as follows [20]:

a. Exponential Distribution Testing.

Hypotheses for Bartlett's Test:

H_0: Failure time data has an Exponential distribution

H_1: Failure time data does not have an Exponential distribution

Test statistic used:

$$B = \frac{2r\left[\ln\left(\frac{1}{r}\right)\sum_{n}^{r} t_i - \left(\frac{1}{r}\right)\sum_{t=1}^{r}\ln t_i\right]}{1 + \left(\frac{r+1}{6r}\right)} \quad (18)$$

where,
B= the Bartlett's Test value
t_i= the i-th failure time
r = the total number of failures

Hypotheses H_0 is accepted if B satisfies the critical region requirements.

$$x^2\left[1 - \left(\left(\frac{\alpha}{2}\right)x - 1\right)\right] < B < x^2\left[\left(\frac{\alpha}{2}x\right) - 1\right] \quad (19)$$

b. Weibull Distribution Testing with Mann's test.

Hypotheses for Mann's Test:

H_0: Failure time data is Weibull-distributed.

H_1: Failure time data is not Weibull-distributed.

$$M = \frac{k1\sum\left[\frac{(\ln t_i + 1) - \ln t_i}{M_i}\right]}{k2\sum\left[\frac{(\ln t_i + 1) - \ln t_i}{M_i}\right]} \quad (20)$$

$$k1 = \frac{r}{2} \quad (21)$$

$$k2 = \frac{r-1}{2} \quad (22)$$

$$M_i = Z_{i+1} - Z_i \quad (23)$$

$$Z_i = \ln\left[-\ln\left(1 - \left(\frac{i - 0{,}5}{n + 0{,}25}\right)\right)\right] \quad (24)$$

where,
t_i = the *i-th* failure interval time
n = the total number of component failures
M_i= the *i-th* Mann value
M = the Weibull distribution value
r = the total data count

If $F_{crit} < M$ then H_1 is accepted. However, $F_{crit} > M$ then H_1 is rejected. The value of F_{crit} d is obtained from the standard F distribution data with $v_1 = 2k_1$ and $v_2 = 2k_2$.

c. Kolmogorov-Smirnov Test.

Hypotheses:

H_0: Inter-failure time data has a normal (lognormal) distribution.

H_1: Inter-failure time data does not have a normal (lognormal) distribution.

Test statistic used:

$$D_n = \max(D_1, D_2) \quad (25)$$

where,

$$D_1 = max\Phi\left(\frac{t_i - \mu}{s}\right) - \left(\frac{t-1}{n}\right) \quad (26)$$

$$D_2 = max\left(\frac{i}{n}\right) - \Phi\left(\frac{t_i - \mu}{s}\right) \quad (27)$$

$$F(t) = \frac{t_i - \mu}{\sigma} \quad (28)$$

$$\mu = \frac{\sum_{i=1}^{n}\ln t_i}{n} \quad (29)$$

$$s = \sqrt{\frac{\sum_{t=1}^{n}(\ln t_i - \mu)^2}{n}} \quad (30)$$

where,
t_i = time to the *i-th* failure
μ = mean time between failures
n = number of data points

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$F(t)$ = *Cumulative Probability*
s = standard deviation
If the value of $D_{crit} > D_n$ than H_0 is accepted. The value of D_{crit} is obtained from the critical value table of the Kolmogorov-Smirnov test for normality.

6. Determining Parameter Estimation
Determining parameter estimation utilizes the Maximum Likelihood Estimator (MLE) method. According to Ebeling, (1997), each distribution has specific size constraints, namely:
   a. Weibull Distribution
   The two parameters used in the Weibull distribution are β *(shape parameter)* and θ *(scale parameter)*.
$$\beta = \frac{n\sum_{i=1}^{n} x_i y_i - \left((\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)\right)}{n\sum_{i=1}^{n} x_i{}^2 - n\sum_{i=1}^{n} y_i{}^2} \quad (31)$$
$$\Phi = e^{-\left(\frac{a}{\beta}\right)} \quad (32)$$
   b. Normal Distribution
   The variables σ and μ are used as parameters for the normal distribution.
$$\mu = \frac{\sum_{i=1}^{n} t_i}{n} \quad (33)$$
$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (t_i - \mu)^2}{n}} \quad (34)$$
   c. Lognormal Distribution
   The values t_{med} (location parameter) and s (shape parameter) are parameters in the lognormal distribution.
$$\mu = \frac{\sum_{i=1}^{n} \ln(t_i)}{n} \quad (35)$$
$$s = \sqrt{\frac{\sum_{i=1}^{n} (\ln t_i - \mu)^2}{n}} \quad (36)$$
$$t_{med} = e^{\mu} \quad (37)$$
   d. Exponential Distribution
   The value λ is used as a parameter in the exponential distribution.
$$\lambda = \frac{n}{T} \quad (38)$$
$$T = \sum_{t_i}^{r} t_i \quad (39)$$

7. *Mean Time To Failure (MTTF)*
Calculate MTTF by dividing the total operational time of the system by the number of failures that occurred during that period, or by dividing the sum of the time between failures and dividing it by the number of failures.
Below are the formulas that can be used to calculate MTTF based on the parameter estimation results according to the type of distribution used:
   a. *Weibull Distribution*
$$MTTF = \Phi.\Gamma\left(1 + \frac{1}{\beta}\right) \quad (40)$$
   b. *Normal Distribution*
$$MTTF = \mu \quad (41)$$
   c. *Lognormal Distribution*
$$MTTF = t_{med}.e^{\frac{s^2}{s}} \quad (42)$$
   d. *Exponential Distribution*
$$MTTF = \frac{1}{\lambda} \quad (43)$$

8. *Mean Time To Repair (MTTR)*
Calculate MTTR by summing all failure incidents' repair time and dividing it by the number of failure incidents. The formula used for calculating MTTR based on the parameter estimation results according to the type of distribution used is the same as the formulas for MTTF, namely Equations 40 to 43.

9. Interval for Part Replacement
To reduce failure rates and minimize downtime in aircraft systems, replacement actions need to be undertaken. This is also aimed at maintaining system performance and preventing the escalation of maintenance costs.

10. Reliability Calculation
This process is carried out at the beginning and end of preventive maintenance actions implemented on the aircraft system. This reliability model assumes that the system returns to its initial condition after undergoing a series of preventive treatments. The formulas used in calculating reliability for each distribution are:
   a. Weibull Distribution
$$R(t) = exp\left[\left(\frac{t}{\Phi}\right)^{\beta}\right] \quad (44)$$
   b. Normal Distribution
$$R(t) = 1 - \Phi\left(\frac{t-\mu}{\sigma}\right) \quad (45)$$
   c. Lognormal Distribution
$$R(t) = 1 - \Phi\left(\frac{1}{s}\ln\frac{t}{t_{med}}\right) \quad (46)$$
   d. Exponential Distribution
$$R(t) = \exp(-\lambda t) \quad (47)$$

The formulas used in calculating preventive maintenance actions for each distribution are:

a. Weibull Distribution

$$R(t-nT) = exp\left[-\left(\frac{t-nT}{\Phi}\right)^{\beta}\right] \tag{48}$$

b. Normal Distribution

$$R(t) = 1 - \Phi\left(\frac{(t-nT)-\mu}{\sigma}\right) \tag{49}$$

c. Lognormal Distribution

$$R(t) = 1 - \Phi\left(\frac{1}{s}\ln\frac{t-nT}{t_{med}}\right) \tag{49}$$

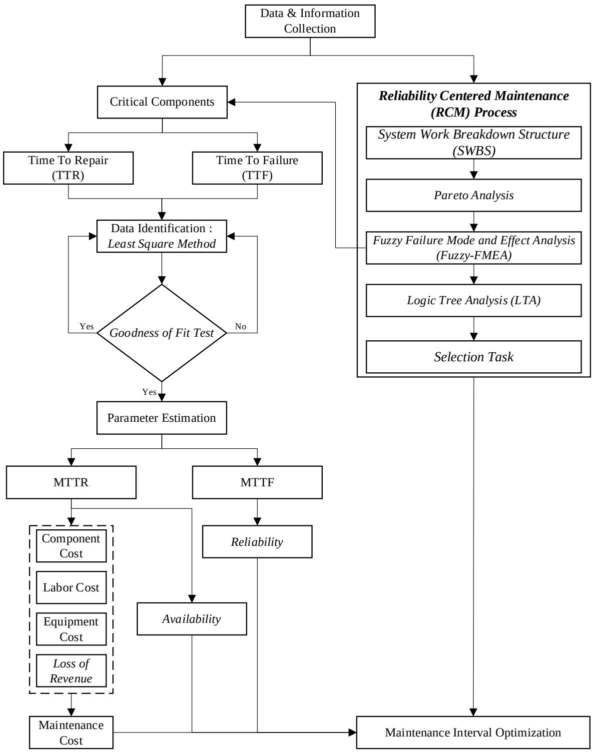

Figure 3. Data Processing Flowchart

d. Exponential Distribution

$$R(t) = \exp(-\lambda(t-nT)) \tag{50}$$

11. Availability Calculation

Availability calculation is used to determine the system's level of availability in meeting operational needs and ensuring that the system can operate effectively and efficiently[21]. The steps for the calculation are as follows:

a. Frequency of Inspection.

$$A(n) = 1 - D(n) \tag{51}$$

$$D(n) = \left(\frac{k}{\mu . n}\right) + \left(\frac{1}{i}\right) \tag{52}$$

b. Interval for Preventive Replacement

$$A(tp) = 1 - [\min D(tp)] \tag{53}$$

where,

$D(tp)$ = Total downtime per cycle

c. Total Availability

$$Availability = A(n) . A(tp) \tag{54}$$

12. Calculate the cost of Preventive Maintenance, Overhaul Maintenance, and Opportunity Cost to determine the magnitude of its efficiency value.
13. Developing a New Maintenance Policy Based on the Results of Optimized Maintenance Interval Calculations.

Results and Discussions

Based on the data analysis, it was observed that maintenance activities conducted outside the main maintenance area in the maintenance division accounted for 21.79%, and maintenance activities comprised 78.21%. The maintenance activities conducted during 2022, as per the System Breakdown Structure (SBS) mapping, consisted of the Airframe and Power Plant systems (Figure 3).

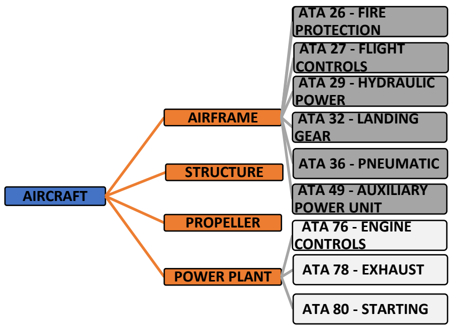

Figure 2. SBS Care Outside the Main Facility 2022

According to the System Breakdown Structure in Figure 3, this can be transformed into a bar chart to facilitate an easier understanding of the maintenance or spare part replacement types based on their frequency conducted outside the main facilities during the 2022 period (Figure 4).

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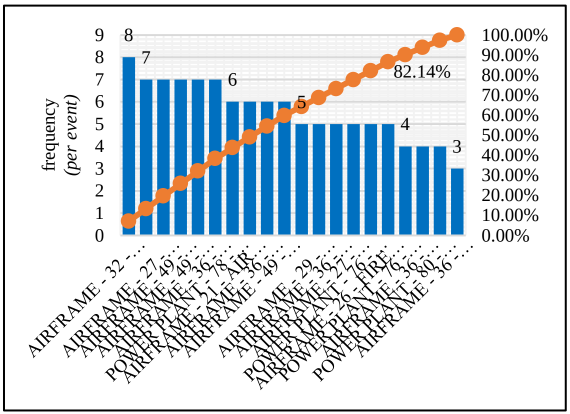

Figure 4. Pareto Part Switching Frequency Diagram 2022

Mode and Effect Analysis (Fuzzy-FMEA) method can be observed in Table 4. Ranks 1-10 in Occurrence, Severity, and Detection were obtained from the FGD (Focus Group Discussion) process, involving experts from the airline company. This table reveals the component classification based on the ranking of Conventional-FMEA and Fuzzy-FMEA with 20 ranks.

Table 5 shows that the primary causes of breakdowns fall under Category A (Issues related to safety), with the most frequent occurrences in the Airframe at 83.04%, predominantly caused by the Auxiliary Power Unit sub-system (G) at 24.11%; and the Power Plant at 16.96%, mainly due to the Engine Controls sub-system (H) at 8.04%.

Based on the results of the FGD (Focus Group Discussion) regarding Current Policy Task and Future Policy Task conducted by a manager from the Line Maintenance department, it can be seen in Table 6 that the current policy is Finding Failure (FF). Therefore, the subsequent policy should be Time Directed (TD) to prevent maintenance activities outside the main maintenance area.

Table 4. Conventional vs Fuzzy-FMEA Processing Results

Component Name	Occurrenc)	Severity	Detection	FMEA Conventional		FMEA-Fuzzy	
				RPN	Rank	RPN	Rank
FCSOV	8	8	9	576	6	891	8
TERMINAL LUG.	3	9	9	243	19	888	17
RUDER TRIM ACTUACTOR (10CC)	9	10	10	900	1	905	1
AUTO SPEED BRAKE ACTUATOR	8	8	8	512	8	895	2
AIR PESSURE GAUGE D/T	7	9	10	630	2	626	20
AUTO BRAKE SHUTTLE VALVE PRESSURE SWITCH	9	8	8	576	3	891	5
SENSE LINE	9	7	7	441	12	891	10
HIGH STAGE REGULATOR	6	9	8	432	16	891	14
BLEED AIR PRECOOLER EXCHANGER	7	8	8	448	11	895	3
HP VALVE	9	7	7	441	13	891	11
BLEED PRESSURE REGULATING VALVE	9	8	8	576	4	891	6
THERMOSTAT SOLENOIDOF ENG #1 (10HA1)	5	7	9	315	18	627	19
FCU	9	7	7	441	14	891	12
IGV ACTUATOR	9	8	8	576	5	891	7
PRESSURE SENSOR (PT)	7	7	8	392	17	895	4
OIL PRESSURE SWITCH	8	7	9	504	10	891	13
LH SWITCH PACK ASSEMBLY	7	7	9	441	15	891	15
AUTOTHROTTLE SWITCHPACK ASSEMBLY	9	9	7	567	7	888	16
R/H A/T SWITCH PACK	7	9	8	504	9	891	9
CB	3	9	9	243	20	888	18

Table 5. LTA (Logic Tree Analysis) Data

Code	Part Name	Frequency	Percentage	Group			
				Percentage	Name	Percentage	Name
A1	FCSOV	6	5,36%	5,36%	A	83,036%	AIR FRAME (ΣA-G)
B1	TERMINAL LUG.	5	4,46%	4,46%	B		
C1	RUDER TRIM ACTUACTOR	5	4,46%	10,71%	C (C1+C2)		
C2	AUTO SPEED BRAKE ACTUATOR	7	6,25%	4,46%	D		

D1	AIR PESSURE GAUGE	5	4,46%	7,14%	E		
E1	AUTO BRAKE SHUTTLE VALVE PRESSURE SWITCH	8	7,14%	26,79%	F (ΣF_{1-6})		
F1	SENSE LINE	3	2,68%	24,11%	G (ΣG_{1-4})		
F2	HIGH STAGE REGULATOR	6	5,36%	8,04%	H (H1+H2)	16,964%	POWER PLANT (ΣH-J)
F3	PRECOOLER EXCHANGER	5	4,46%	5,36%	I		
F4	HP VALVE	7	6,25%	3,57%	J		
F5	BLEED PRESSURE REGULATING VALVE	5	4,46%	*100,000%*			*Total*

Code	Part Name	Frequency	Percentage
F6	THERMOSTAT SOLENOID (10HA1)	4	3,57%
G1	FCU	6	5,36%
G2	IGV ACTUATOR	7	6,25%
G3	PRESSURE SENSOR (PT SENSOR)	7	6,25%
G4	OIL PRESSURE SWITCH	7	6,25%
H1	LH SWITCH PACK ASSEMBLY	4	3,57%
H2	AUTOTHROTTLE SWITCHPACK	5	4,46%
I1	SWITCH PACK	6	5,36%
J1	CB	4	3,57%

Table 6. Comparison of Care Policies

Part Name	Code	Failure Mode	Current Policy Task	Future Policy Task
AIRFRAME - 26 - FIRE PROTECTION - TERMINAL LUG.	B1	Burn Cloud Putus	FF	E.G.
AIRFRAME - 36 - PNEUMATIC - SENSE LINE	F1	Bocor	FF	E.G.
AIRFRAME - 36 - PNEUMATIC - HP VALVE	F4	Cats Loose	FF	E.G.
AIRFRAME - 49 - AUXILIARY POWER UNIT- FCU	G1	Slow Response Does not detect flow	FF	E.G.
POWER PLANT - 76 - ENGINE CONTROLS - AUTOTHROTTLE SWITCHPACK ASSEMBLY	H2	Unbalanced right & left Less sensitive	FF	E.G.
POWER PLANT - 80 - STARTING - CB	J1	Burn Loss Power	FF	E.G.
AIRFRAME - 21 - AIR CONDITIONING - FCSOV	A1	Loose	FF	E.G.
AIRFRAME - 27 - FLIGHT CONTROLS - RUDER TRIM	C1	System error on warning	FF	E.G.
AIRFRAME - 32 - LANDING GEAR - AUTO BRAKE SHUTTLE VALVE PRESSURE SWITCH	E1	Disconnect cannot detect Burn	FF	E.G.
AIRFRAME - 36 - PNEUMATIC - BLEED PRESSURE REGULATING VALVE	F5	Cats Loose	FF	E.G.
AIRFRAME - 49 - AIRBORNE AUXILIARY POWER - IGV ACTUATOR	G2	Cats Cannot detect command	FF	E.G.
AIRFRAME - 49 - AIRBORNE AUXILIARY POWER - PRESSURE SENSOR (PT)	G3	Cannot detect command Putus	FF	E.G.
AIRFRAME - 49 - AIRBORNE AUXILIARY POWER - OIL PRESSURE SWITCH	G4	Cats Unable to detect	FF	E.G.
POWER PLANT - 76 - ENGINE CONTROLS - LH SWITCH PACK ASSEMBLY	H1	Unbalanced right & left Less sensitive	FF	E.G.
AIRFRAME - 27 - FLIGHT CONTROLS - AUTO SPEED BRAKE ACTUATOR	C2	Bocor Unbalanced right & left	FF	E.G.
AIRFRAME - 36 - PNEUMATIC - BLEED AIR PRECOOLER EXCHANGER	F3	Bocor Broken seal	FF	E.G.
POWER PLANT - 78 - ENGINE EXHAUST - R/H A/T SWITCH PACK	I1	Unbalanced right & left Less sensitive	FF	E.G.
AIRFRAME - 29 - HYDRAULIC POWER - AIR PRESSURE	D1	Bocor	FF	E.G.
AIRFRAME - 36 - PNEUMATIC - THERMOSTAT	F6	Burn	FF	E.G.

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SOLENOIDOF ENG #1 (10HA1)		Unable to detect Putus		
AIRFRAME - 36 - PNEUMATIC - HIGH STAGE REGULATOR	F2	Cannot detect command Unable to send command	FF	E.G.

The results of the Time to Failure (TTF) data processing using Minitab 19 software for each component undergoing maintenance, including determining the data distribution type, conducting Goodness of Fit tests, Parameter Estimation, and MTTF, are presented in Table 7.

In processing Time to Repair (TTR) data for initial spare part replacement, the type of data distribution was determined, Goodness of Fit tests were conducted, and Parameter Estimation was performed, resulting in the MTTR values as shown in Table 8.

Following discussions with the airline (Manager of Line Maintenance), which indicated that maintenance activities could be shifted to a Time Directed (TD) approach, validation was carried out using simulations of past data focusing only on repair time (MTTR), as seen in Table 9.

The determination of maintenance intervals transitioning from Finding Failure (FF) to Time Directed (TD) is depicted in Table 10. According to this table, an airline can perform scheduled maintenance. This data will serve as input from the maintenance division to the planning division within the regular operational department.

Table 7. Distribution, Parameter Estimation and MTTF

Component Code	Distribution	Estimate Parameter		MTTF *(hour)*
A1	Lognormal	μ S	28.530,300 616,018	28.530,300
B1	Lognormal	μ S	88.256,800 6.255,530	88.256,800
C1	Normal	μ σ	16.671,400 1.149,360	16.671,400
C2	Normal	μ σ	30.534,600 806,491	30.534,600
D1	Weibull	η β	40.490,800 16,047	39.181,600
E1	Weibull	η β	18.357,000 28,691	18.009,000
F1	Normal	μ σ	23.715,000 3.986,020	23.715,000
F2	Normal	μ σ	48.833,300 2.580,080	48.833,300
F3	Weibull	η β	58.803,800 4,949	53.959,800
F4	Normal	μ σ	18.469,700 551,820	18.469,700
F5	Normal	μ σ	14.425,800 1.069,070	14.425,800
F6	Lognormal	μ S	61.499,300 5.240,350	61.499,300
G1	Lognormal	μ S	22.152,500 1.428,100	22.152,500
G2	Weibull	η β	18.112,600 74,818	17.976,000
G3	Lognormal	μ S	40.213,400 1.680,120	40.213,400
G4	Weibull	η β	24.118,600 19,120	23.452,800
H1	Lognormal	μ S	36.754,400 4.997,460	36.754,400
H2	Weibull	η β	16.751,400 10,721	15.982,500
I1	Lognormal	μ S	41.368,000 4.192,560	41.368,000
J1	Lognormal	μ S	90.358,200 9.879,840	90.358,200

Table 8. Distribution, Parameter Estimation and Initial MTTR

Component Code	Distribution	Estimate Parameter		MTTR *(hour)*
A1	Weibull	η β	66,261 20,093	64,512
B1	Weibull	η β	62,778 8,862	59,406
C1	Weibull	η β	66,441 18,448	64,547
C2	Lognormal	μ S	57,521 6,270	57,521
D1	Weibull	η β	59,655 11,374	57,051
E1	Weibull	η β	65,149 7,974	61,344
F1	Weibull	η	63,807	59,271

		β	6,142	
F2	Weibull	η	66,469	64,187
		β	15,003	
F3	Weibull	η	68,728	65,783
		β	11,628	
F4	Lognormal	μ	55,967	55,967
		S	7,110	
F5	Weibull	η	63,836	60,129
		β	8,031	
F6	Lognormal	μ	55,511	55,511
		S	6,304	
G1	Lognormal	μ	60,777	60,777
		S	8,608	
G2	Lognormal	μ	60,790	60,790
		S	4,998	
G3	Normal	μ	61,903	61,903
		σ	6,888	
G4	Lognormal	μ	56,907	56,907
		S	5,823	
H1	Weibull	η	64,869	60,716
		β	7,078	
H2	Normal	μ	56,796	56,796
		σ	5,204	
I1	Lognormal	μ	60,154	60,154
		S	8,702	
J1	Weibull	η	58,957	56,494
		β	11,976	

Table 9. Distribution, Parameter Estimation and MTTR Improvements

Component Code	Distribution	Estimate Parameter		MTTR *(hour)*
A1	Weibull	η	2,214	2,158
		β	21,045	
B1	Weibull	η	1,897	1,800
		β	9,468	
C1	Lognormal	μ	5,012	5,012
		S	0,316	
C2	Lognormal	μ	4,922	4,922
		S	0,661	
D1	Weibull	η	0,896	0,863
		β	13,609	
E1	Lognormal	μ	2,692	2,692
		S	0,219	
F1	Weibull	η	1,960	1,913
		β	22,705	
F2	Weibull	η	1,831	1,763
		β	13,705	
F3	Weibull	η	3,571	3,445
		β	14,507	
F4	Lognormal	μ	2,775	2,775
		S	0,165	
F5	Lognormal	μ	2,299	2,299
		S	0,353	
F6	Normal	μ	1,717	1,717
		σ	0,230	
G1	Weibull	η	1,108	1,022
		β	5,408	
G2	Normal	μ	2,424	2,424
		σ	0,388	
G3	Lognormal	μ	1,707	1,707
		S	0,189	
G4	Lognormal	μ	0,909	0,909
		S	0,109	
H1	Lognormal	μ	6,341	6,341
		S	0,311	
H2	Lognormal	μ	6,345	6,345
		S	0,262	
I1	Lognormal	μ	6,460	6,460
		S	0,225	
J1	Weibull	η	1,009	0,965
		β	11,453	

Table 10. Aircraft Maintenance Time Interval

Component Code	t *(hour)*	*(day)*	*(weeks)*	*(years)*
F5	15.000	782	111	2
C1	17.000	886	126	2
H2	17.000	886	126	2
G2	18.100	943	134	2
E1	18.500	964	137	2
F4	18.800	980	139	2
G1	23.000	1198	170	3
G4	24.500	1277	181	3
F1	26.000	1355	192	3
A1	29.000	1511	215	4
C2	31.000	1615	230	4
H1	40.000	2084	296	5
D1	41.000	2136	304	5
G3	41.000	2136	304	5
I1	43.000	2240	319	6
F2	50.000	2605	371	7
F3	60.000	3125	445	8
F6	64.000	3334	474	9
B1	90.000	4688	667	12
J1	95.000	4948	704	13

The MTTF data in Table 7 were transformed into component reliability data with the aid of Minitab software, producing a data distribution overview plot. As a result, the reliability sequence of components appears parallel due to the application of the 'OR' logic by the Logic Tree Analysis (LTA) data in Table 5. This was then transformed for ease of visualization, as shown in Figure 5.

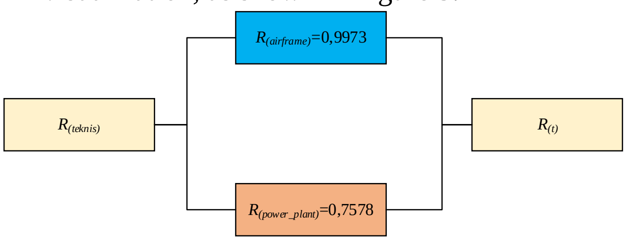

Figure 5. Reliability Sistem Diagram

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Based on the data in Figure 5, the reliability value of the system was calculated as follows:

$$R_{(teknis)} = 1 - \left(\left(1 - R_{(airframe)}\right).\left(1 - R_{(power_{plant})}\right)\right)$$
$$= 1 - \left((1 - 0{,}9973).(1 - 0{,}7578)\right)$$
$$= 1 - (\ 0{,}0027\ .\ 0{,}2422\ ) = 0{,}9993$$

The calculation results indicate that the system reliability is 0.9993 or 99.93%.

The calculation of the availability value for each component was derived from the MTTF data, initial MTTR, and MTTR after repair. The table shows the lowest and highest initial availability values for the Airframe 36 Pneumatic Bleed Pressure Regulating Valve at 99.585% and Power Plant 80 Starting CB at 99.938%, respectively. The lowest and highest repair availability values are for the Power Plant 76 Engine Controls-Autothrottle Switchpack Assembly at 99.960% and Power Plant 80 Starting CB at 99.999%, respectively (Table 11).

Table 11. Initial Availability and Repair

Component Code	Availability	
	Beginning $\left(\frac{MTTF}{(MTTF + MTTR_{perbaikan})}\right)$	End $\left(\frac{MTTF}{(MTTF + MTTR_{perbaikan})}\right)$
A1	99,774%	99,992%
B1	99,933%	99,998%
C1	99,614%	99,970%
C2	99,812%	99,984%
D1	99,855%	99,998%
E1	99,661%	99,985%
F1	99,751%	99,992%
F2	99,869%	99,996%
F3	99,878%	99,994%
F4	99,698%	99,985%
F5	99,585%	99,984%
F6	99,910%	99,997%
G1	99,726%	99,995%
G2	99,663%	99,987%
G3	99,846%	99,996%
G4	99,758%	99,996%
H1	99,835%	99,983%
H2	99,646%	99,960%
I1	99,855%	99,984%
J1	99,938%	99,999%

The calculation of maintenance costs encompasses the total cost, including component expenses, labor costs, equipment costs, and other related expenses. Meanwhile, calculating losses caused by maintenance activities based on the current Finding Failure policy covers the total cost of opportunity loss. Details of these expenses are presented in Table 12.

Table 12. Maintenance and Repair Costs

(in thousands)

	Item	Qty	Unit	Total
A.	**Maintenance**			
1	Number of personnel dispatch activities	402	times/ years	
2	Number of personnel	2	person/ delivery	
3	Personnel Costs	1	year	1.989.900
	Accommodation	1	Delivery	
	Money	1	person	
	Meal Money	1	person	
4	Other	10%		198.990
	Total			***2.188.890***
B.	**Therapy**			
1	Number of personnel dispatch activities	112	times/ years	
2	Number of personnel	2	person/ delivery	
3	Personnel Costs	1	year	554.400
	Accommodation	1	Delivery	
	Money	1	person	
	Meal Money	1	person	
4	Sparepart (Tax Include)	1	year	13.742.578,78
5	Other	10%		1.429.697,88
	Total			***15.726.676,65***
C.	**Opportunity Loss Maintenance**			
1	Asumsi			
	Flight	1	person	
	Passenger capacity	189	seat	
	Occupancy	50%		
	Average flight time	2	jam	
2	Total Time To Repair (TTR)	920	Hours/ year	
3	Flying Loss	377	flight	35.459.055,45
4	Other	10%		3.545.905,55
	Total			***39.004.961,00***
D.	**Early Opportunity Loss Treatment**			
1	Asumsi			
	Flight	1	person	
	Passenger capacity	189	seat	
	Occupancy	50%		
	Average flight time	2	jam	
2	Total Time To Repair (TTR)	6.740	Hours/ year	
3	Flying Loss	2.762	flight	259.782.257,70
4	Other	10%		25.978.225,77
	Total			***285.760.483,47***
E.	**Opportunity Loss Final Treatment (Repair)**			
1	Asumsi			
	Flight	1	person	
	Passenger capacity	189	seat	
	Occupancy	50%		
	Average flight time	2	jam	
2	Total Time To Repair (TTR)	320	Hours/ year	
3	Flying Loss	130	flight	12.227.260,50
4	Other	10%		1.222.726,05

	Total	*13.449.986,55*
F.	**Initial Maintenance Cost** (A+B+C+D)	**342.681.011,12**
G.	**Repair Maintenance Cost** (A+B+C+E)	**70.370.514,20**

The initial costs borne by the company for maintenance were approximately IDR 342.68 billion, which decreased to IDR 70.37 billion per year following improvements. The reliability of the aircraft system is very high (99.93%), with a significant increase in component availability after maintenance, from 99.780% to 99.989%. This indicates that the maintenance and care strategy employed effectively maintains the reliability and availability of aircraft components, emphasizing a data-driven approach to determine optimal maintenance intervals.

This study resulted in a policy of 20 maintenance activities, transitioning from a previous Finding Failure (FF) policy to a Time Directed (TD) policy. This change is not significantly different from a previous study that resulted in 44 maintenance activities, changing from 16 TD and 28 FF policies to 2 TD, 16 Condition Directed (CD), and 26 FF policies[22].

In calculating risk value using the fuzzy-FMEA method, 20 potential risks of damage were identified with Fuzzy FMEA. The airframe sub-system with the TERMINAL LUG component had the highest Fuzzy-RPN value of 867, while the Conventional-RPN value was 243, a difference of 71.97%. Meanwhile, a previous study identified 16 potential risks from various sub-system damages in Fuzzy FMEA, where the electrical subsystem had the highest RPN value of 168, and the Fuzzy RPN was 117, with a difference between RPN and FRPN of 30.36% [23].

The aspect of efficiency assessment after implementing RCM in this study showed a cost
saving of 79.47%, from IDR 342,681,011,1 18.60 to IDR 70,370,514,198.60, which is more effective than the previous study, which only achieved a cost saving of 21.77%, from IDR 4,968,017,280 to IDR 3,886,270,078.76 [24].
This study has several limitations in its implementation, including:

1. The study was conducted using data sourced from only one main facility area.
2. The simulation experiments in this study only used data from past mechanic worktime reports in spare part replacement activities.
3. The calculation of opportunity loss costs used an occupancy assumption of 50% of the seat capacity without using actual data checked for distribution type and past data testing.
4. This study focused only on a specific aircraft type, the Boeing 737 Series.

Conclusions

This study shows that the primary factor causing maintenance outside the main facility is the Finding Failure (FF) maintenance policy. This policy leads to work falling into unscheduled maintenance, making maintenance activities unpredictable and thus resulting in damage outside the main facility areas (Batam, Cengkareng, and Surabaya).

The incidence of maintenance outside the main hangar facility can be eliminated by changing the policy from Finding Failure (FF) to Time Directed (TD). This change has been proven to significantly reduce the costs borne by the company, from initially IDR 342.681 billion to IDR 70.370 billion, a saving of 79.47%.

The fuzzy-FMEA method has provided more accurate risk identification results than conventional-FMEA. Therefore, developing and integrating the Fuzzy-FMEA method into future aircraft maintenance systems is recommended.

This study demonstrates significant differences in risk identification and maintenance policies compared to previous research. This presents an opportunity for further comparative studies, which can aid in refining the maintenance model for the aviation industry.

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