Optimal Imperfect Maintenance Policy of Aircraft Component Considering the Effect of Human Factors

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Abstract: - This paper focuses on the optimization of an imperfect maintenance policy with human factors of aircraft components. A nonlinear stochastic programming model is established to maximize the availability of components. The existence conditions of the optimal preventive maintenance interval are derived, and the effectiveness of the proposed model is verified through a number of examples.

Key-Words: - Imperfect Maintenance Policy, Human Error Factors, Stochastic Optimization.

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1 Introduction

In recent decades, with the development of the civil aviation transportation industry, the number of aircraft has been increasing rapidly, which has brought great pressure to the maintenance management of aviation enterprises. Aircraft structural damage or system failures may lead to flight delays or cancellations, which cause economic losses and a bad reputation for airlines. Therefore, to achieve high safety and reliability of civil aircraft, a classic preventive maintenance (PM) policy is usually adopted in this stage.

In the 1980s, [1], proposed that preventive maintenance has two effects: "maintenance as new" and "maintenance as old", which are called perfect maintenance and imperfect maintenance, respectively. Due to the influence of human factors, technical support, service environment, etc., in the aircraft maintenance process, imperfect maintenance has become a common type in preventive maintenance. Especially, the human errors of maintenance personnel in the aircraft maintenance process make the rate of flight incident precursors remain high. Therefore, the influence of human factors should be considered when optimizing aircraft maintenance strategies.

Regarding the research on imperfect maintenance strategies, [2], first used the residual life model to describe the degradation process of the system after imperfect maintenance. The study [3] discussed and summarized various processing methods and optimal decisions for imperfect maintenance. The study [4], obtained the optimal length of PM interval and the optimal number of PM performed before system replacement through the minimum cost rate function for imperfect preventive maintenance. The study [5], explored the impact of imperfect maintenance on repairable equipment and transformed equipment reliability and maintainability parameters into availability model parameters. The study [6], proposed a new imperfect maintenance model for degraded systems, which is used to provide the optimal number of imperfect maintenance operations for each life cycle.

The study [7] concluded through case studies that human error is one of the main causes of imperfect aircraft maintenance, indicating that human error is a frequent source of accidents and failures in complex technical systems. The study [8], developed a method to analyze human errors and formulated preventive measures based on the analysis results, enabling airlines to improve their maintenance systems. The study [9], conducted a statistical analysis of 58 samples of safety incidents caused by helicopter maintenance and found that these accidents had a high probability of being triggered by human error factors, emphasizing the impact of human error on maintenance effects. The study [10], analyzed and emphasized how human factors lead to errors, how to minimize them in daily aviation practice, and that analyzing the root causes after any incident helps prevent future errors.

However, human errors cannot be avoided. In [11], [12], the studies proposed a model for human error probability analysis, aiming to evaluate the errors caused by human factors in different situations. This paper considers three preventive maintenance consequences that may be caused by human factors in the aircraft maintenance process: (1) imperfect maintenance with unchanged system failure rate, (2) perfect maintenance with the system restored as new and (3) failed maintenance with system failure. An optimization model for preventive maintenance of aircraft components with maximum availability is established. The weights of various human factors are evaluated based on the analytic hierarchy process to determine the probabilities of the three maintenance consequences. Validation via case studies and sensitivity analyses confirms model efficacy, enabling data-driven maintenance plan adjustments for aviation operators.

2 Model Formulation

For the convenience of modeling, symbols and assumptions are given first.

2.1 Symbols

T: Preventive maintenance cycle of aircraft component, decision variable

T^*: The optimal preventive maintenance time to maximize the availability of the aircraft component

q_1: The probability of imperfect preventive maintenance, that is, the probability that the failure rate of aircraft components remains unchanged after maintenance

q_2: The probability of perfect preventive maintenance, that is, the probability that the system will return to a new state after maintenance of the aircraft component

q_3: The probability of failure of preventive maintenance, that is, the probability of failure of the system after maintenance of the aircraft component

α_1: Mean renewal time of aircraft component under failure repair

α_2: Mean renewal time of aircraft component under unsuccessful repair

α_3: Mean renewal time of aircraft component under perfect repair

$F(t)$: The cumulative failure probability of the aircraft component before time t

$F(iT)$: The cumulative failure probability before the i-th PM cycle of the aircraft component, i=1,2,…

$f(iT)$: Instantaneous failure probability density at the i-th maintenance time point

$\overline{F}(t)$: The probability that the system survives until time t

$\overline{F}(iT)$: The probability that the system survives until the i-th PM cycle of the aircraft component, i=1,2,…

$l(T;q_1,q_2,q_3)$: Mean failure time of aircraft component in a renewal cycle

$A(T;q_1,q_2,q_3)$: Mean availability of aircraft component in a renewal cycle

μ: Mean failure time of aircraft component in a renewal cycle, where $T=\infty$.

2.2 Description and Assumptions of the Problem

This section considers a single-component system that performs preventive maintenance at fixed periodic points $nT(n=1,2,\ldots)$. The maintenance process is shown in Figure 1.

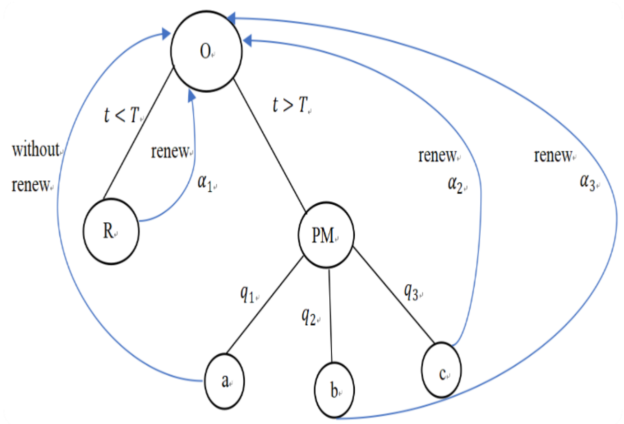

Fig. 1: Preventive maintenance flow graph

Source: created by the authors

In Figure 1, Symbol ‘O’ represents the initial state of aircraft structural components, ‘R’ represents the immediate maintenance when the system fails, ‘PM’ represents preventive maintenance, ‘a’ represents imperfect preventive maintenance, ‘b’ represents perfect preventive maintenance, and ‘c’ represents failed preventive maintenance. Given the following assumptions:

The system is in good condition at the start of operation, is repairable, and can run indefinitely.

When the system fails before the fixed periodic point $iT(i=1,2,\ldots)$, minor repairs will be carried out immediately, assuming that the effect is perfect.

The system performs preventive maintenance at fixed periodic points $iT(i=1,2,\ldots)$ with $0<T\leq\infty$. It is assumed that the consequences of preventive maintenance (PM) caused by human factors will occur in one of the following situations:

(i) The system maintains the failure rate unchanged with probability q_1, that is, preventive maintenance is imperfect.

(ii) The system is restored to its original state with a probability of q_2, that is, preventive maintenance is perfect.

(iii) The system fails with probability q_3, that is, preventive maintenance fails, and $q_1+q_2+q_3=1$ and $q_2>0$.

Due to the complexity and suddenness of system failure, as well as the controllability of operation errors in preventive maintenance, the repair of human operation errors is usually more controllable than random faults, and the time is shorter, so that $\alpha_1\geq\alpha_2+\alpha_3$.

Since the short maintenance time contributes very little to the overall availability of the system, the model can be simplified by ignoring it, and the effect of the maintenance strategy can still be accurately reflected. Therefore, the time used for imperfect maintenance can be ignored.

2.3 Model Formulation

This section considers an imperfect preventive maintenance renewal model for a single-component system of an aircraft. As can be seen from maintenance flowchart 1, there are three renewal scenarios in this system:

Case I: renew under failure repair

It means that the previous (i-1) maintenance is "imperfect maintenance" (the probability is q_1^{i-1}), then the failure maintenance occurs in the i-th maintenance cycle, and its probability is:$\int_{(i-1)T}^{iT} dF(t)$,then the probability that the system can be renewed due to fault maintenance is:

$$\sum_{i=1}^{\infty} q_1^{i-1} \int_{(i-1)T}^{iT} \mathrm{d}\,F(t) = (1-q_1)\sum_{i=1}^{\infty} q_1^{i-1} F(iT) \tag{1}$$

Case II: renew under perfect repair

It means that the previous (i-1) maintenance is "imperfect maintenance" (the probability is q_1^{i-1}), and the probability of perfect maintenance at the i-th time is q_2, then the probability of system updating through perfect preventive maintenance is:

$$q_2 \sum_{i=1}^{\infty} q_1^{i-1} \bar{F}(iT) \tag{2}$$

Case III: renew under failure repair

It means that (i-1) maintenance times are "imperfect maintenance" (the probability is q_1^{i-1}), and the system has the probability of updating through maintenance after maintenance failure. If the maintenance is successful at the i-th time (the probability is q_3), then the probability of the system updating through maintenance after maintenance failure is:

$$q_3 \sum_{i=1}^{\infty} q_1^{i-1} \overline{F}(iT) \tag{3}$$

With (1) + (2) + (3) =1.

A renewal cycle

From (1), (2), and (3), we can get the expected value of the system, [13], from time t=0 to renew the normal running time:

$$\sum_{i=1}^{\infty} q_1^{i-1} \int_{(i-1)T}^{iT} t \,\mathrm{d}\, F(t) + (q_2+q_3)\sum_{i=1}^{\infty} i\,T q_1^{i-1}\overline{F}(iT) = (1-q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{iT}\overline{F}\,(t)\mathrm{d}\,t \tag{4}$$

Mean Time To Repair

The average time to repair in a renewal cycle is denoted by $l(T;q_1,q_2,q_3)$ and consists of three parts:

(1)The time of failure in the i-th preventive cycle $q_1^{i-1}\int_{(i-1)T}^{iT} tdF(t)$

(2)The average time to failure for the i-th preventive maintenance is the perfect maintenance $q_1^{i-1}\overline{F}(iT)q_2(iT + l(T;q_1,q_2,q_3))$;

(3)When the i-th preventive maintenance is a failed maintenance, it is only counted in the current cycle time, iT, that is $q_1^{i-1}\overline{F}(iT)q_3 iT$.

The Mean Time Between Failures is:

$$l(T;q_1,q_2,q_3) = \sum_{i=1}^{\infty}\left\{q_1^{i-1}\int_{(i-1)T}^{iT} tdF(t) + q_1^{i-1}\overline{F}(iT)\left[q_2\left(iT + l(T;q_1,q_2,q_3)\right) + q_3 iT\right]\right\}$$

Simplify to:

$$l(T;q_1,q_2,q_3) = \frac{(1-q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{iT}\overline{F}(t)\mathrm{d}t}{1-q_2\sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(iT)} \tag{5}$$

Availability

Availability $= \frac{\text{run}}{\text{total time (run + fix)}}$, where the fix time consists of three parts:

(1)Time to fix a fault (the time required to fix each fault α_1, the expected time of all cycles is added):$\alpha_1(1-q_1)\sum_{i=1}^{\infty} q_1^{i-1} F(iT)$

(2)Maintain perfect repair time (each successful repair time α_3, the expected time of all cycles is added):$\alpha_3 q_2 \sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(iT)$

(3)Maintenance failure repair time (each failure requires repair time α_2, the expected time of all cycles is added):$\alpha_2 q_3 \sum_{i=1}^{\infty} q_1^{i-1}\,\overline{F}(iT)$

The availability can be obtained as follows:

$$A(T;q_1,q_2,q_3) = \frac{(1-q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{iT}\overline{F}(t)dt}{\left[(1-q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{iT}\overline{F}(t)dt + \alpha_2 q_3\sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(iT) + \alpha_1(1-q_1)\sum_{i=1}^{\infty} q_1^{i-1}F(iT) + \alpha_3 q_2\sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(iT)\right]} \tag{6}$$

3 Existence of Solution

In our model, the optimal preventive maintenance time T_1 that maximizes availability is considered, and it is proved that under certain conditions, T_1 can be determined by a unique solution of an equation.

First, we seek an optimal preventive maintenance time T_1 to maximize the mean time between failures $l(T;q_1,q_2,q_3)$. Here, we first present a theorem:

Theorem 1 (Existence of solution) For formula (5), let $H(T;q_1) \equiv \frac{\sum_{i=1}^{\infty} q_1^{i-1} i f(iT)}{\sum_{i=1}^{\infty} q_1^{i-1} i\overline{F}(iT)}$, If satisfied $H(T;q_1)$ strictly increasing;

When $T\to 0$ and $T\to\infty$, the function values of formula (5) are respectively $\frac{1}{1-q_1}$ and $\frac{\mu H(\infty;q_1)}{1-q_1}$, and $\frac{1}{1-q_1} \leq \frac{1}{q_2} \leq \frac{\mu H(\infty;q_1)}{1-q_1}$, further if $H(\infty;q_1) > \frac{1-q_1}{\mu q_2}$;

Then $l(T;q_1,q_2,q_3)$ has a finite and unique minimum solution T_1. It is determined by $\frac{1}{q_2} =$

$\frac{l(T_1;q_1,q_2,q_3)H(T_1;q_1)}{1-q_1}$.

Prove:

due to $\sum_{i=1}^{\infty} q_1^{i-1} = \frac{1}{1-q_1}$, $\int_0^{\infty} \overline{F}(t)dt = \int_0^{\infty} tdF(t) = \mu$, $\overline{F}(0) = 1$

As we know,

$$l(0; q_1, q_2, q_3) \equiv \lim_{T\to 0}(T; q_1, q_2, q_3)$$

$$= \frac{(1-q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^0 \overline{F}(t)\,\mathrm{d}t}{1-q_2\sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(0)}$$

$$= 0$$

$$l(\infty; q_1, q_2, q_3) \equiv \lim_{T\to\infty} l\,(T; q_1, q_2, q_3)$$

$$= \frac{(1-q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{\infty} \overline{F}\,(t)\mathrm{d}\,t}{1-q_2\sum_{i=1}^{\infty} q_1^{i-1}\overline{F}\,(\infty)}$$

$$= \mu$$

Therefore, there exists a positive $T_1(0<T_1 \leq \infty)$,which can make $l(T;q_1,q_2,q_3)$ reach the minimum value.Taking the derivative of $l(T;q_1,q_2,q_3)$ with respect to T and setting it equal to zero, [14], we get:

$$H(T; q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{iT}\overline{F}(t)\mathrm{d}t + \sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(iT) = \frac{1}{q_2} \tag{7}$$

among:

$$H(T; q_1) \equiv \frac{\sum_{i=1}^{\infty} q_1^{i-1} if(iT)}{\sum_{i=1}^{\infty} q_1^{i-1} i\overline{F}(iT)} \tag{8}$$

When $H(T;q_1)$ is strictly increasing, when the left side of (7) is T=0:

$$H(0; q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{0}\overline{F}(t)\mathrm{d}t + \sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(0)$$

$$= \frac{1}{1-q_1}$$

$T = \infty$:

$$H(\infty; q_1)\sum_{i=1}^{\infty} q_1^{i-1}\int_0^{\infty}\overline{F}(t)\mathrm{d}t + \sum_{i=1}^{\infty} q_1^{i-1}\overline{F}(\infty)$$

$$= \frac{\mu H(\infty; q_1)}{1-q_1}$$

Then the left side of (7) strictly increases from $\frac{1}{1-q_1}$ to $\frac{\mu H(\infty;q_1)}{1-q_1}$ is that $\frac{1}{1-q_1} \leq \frac{1}{q_2} \leq \frac{\mu H(\infty;q_1)}{1-q_1}$. The discussion is divided into the following two scenarios:

(I) If $H(T;q_1)$ is strictly increasing and $H(\infty; q_1) > \frac{1-q_1}{\mu q_2}$, then there exists a finite and unique T_1 that satisfies equation (7), such that $\frac{1}{q_2} = \frac{l(T_1;q_1,q_2,q_3)H(T_1;q_1)}{1-q_1}$. The resulting mean time between failures is:

$$l(T_1; q_1, q_2, q_3) = \frac{1-q_1}{q_2 H(T_1; q_1)}$$

(II) If $H(T;q_1)$ is not increasing, or $H(T;q_1)$ is strictly increasing and $H(\infty; q_1) \leq \frac{1-q_1}{\mu q_2}$, then $T_1=\infty$; that is, preventive maintenance should not be performed, the mean time between failures is μ, meaning there is no finite and unique solution at this point.

Next, we seek an optimal preventive maintenance time T^* to maximize availability $A(T;q_1,q_2,q_3)$. Taking the derivative of $A(T;q_1,q_2,q_3)$ with respect to T and setting it to zero yields:

$$\mathrm{H}(\mathrm{T}; \mathrm{q}_1)\sum_{\mathrm{i}=1}^{\infty} \mathrm{q}_1^{\mathrm{i}-1}\int_0^{\mathrm{iT}}\overline{\mathrm{F}}(\mathrm{t})\mathrm{dt} + \sum_{\mathrm{i}=1}^{\infty} \mathrm{q}_1^{\mathrm{i}-1}\overline{\mathrm{F}}(\mathrm{iT}) = \frac{\alpha_1}{\alpha_1(1-\mathrm{q}_1)-\alpha_2\mathrm{q}_3-\alpha_3\mathrm{q}_2} \tag{9}$$

Because $\alpha_1 \geq \alpha_2+\alpha_3$, we have $\alpha_1(1-q_1) > \alpha_2 q_3+\alpha_3 q_2$.

Based on the above derivation, considering both equations (7) and (9), we can obtain the optimal preventive maintenance time to maximize availability.

4 Numerical Example

4.1 Optimal Solution given the Failure Distribution Function

Consider a triple redundant system composed of three aircraft components, where the system fails when two or more units malfunction. This system is a "three-out-of-two" system. Let the distribution of system failures be $\overline{F}(T) = 3e^{-2T} - 2e^{-3T}$. The average system failure time μ = 5/6. Substituting this into equation (8) yields

$$H(T;q_1) = \frac{6\sum_{i=1}^{\infty} q_1^{i-1} i\left(\mathrm{e}^{-2iT} - \mathrm{e}^{-3iT}\right)}{\sum_{i=1}^{\infty} q_1^{i-1} i(3\mathrm{e}^{-2iT} - 2\mathrm{e}^{-3iT})}$$

among,

$H(0;q_1) = 0$

$H(\infty;q_1) = 2$

due to

$$\frac{\mathrm{d}H(T;q_1)}{6\mathrm{d}t} = \frac{1}{D}\left[6\sum_{i=1}^{\infty} q_1^{i-1} i^2 (\mathrm{e}^{-2iT} - \mathrm{e}^{-3iT}) \sum_{i=1}^{\infty} q_1^{i-1} i(\mathrm{e}^{-2iT} - \mathrm{e}^{-3iT}) - \sum_{i=1}^{\infty} q_1^{i-1} i^2 (2\mathrm{e}^{-2iT} - 3\mathrm{e}^{-3iT}) \sum_{i=1}^{\infty} q_1^{i-1} i(3\mathrm{e}^{-2iT} - 2\mathrm{e}^{-3iT})\right]$$

$$= \frac{1}{D}\left[\sum_{j=1}^{\infty}\sum_{i=1}^{\infty} q_1^{i+j-2} (j^2 i)(3\mathrm{e}^{-jT} - 2\mathrm{e}^{-iT})\mathrm{e}^{-2(i+j)T}\right] > 0$$

among,

$$D \equiv \left[\sum_{i=1}^{\infty} q_1^{i-1} i\left(3\mathrm{e}^{-2iT} - 2\mathrm{e}^{-3iT}\right)\right]^2$$

Therefore, $H(T;q_1)$ is strictly increasing from 0 to 2.

Therefore, if $1 - q_1 > (5/2)\frac{(\alpha_2 q_3 + \alpha_3 q_2)}{\alpha_1}$, there exists a finite and unique T^* satisfying:

$$\frac{H(T^*;q_1)}{6}\left\{\sum_{i=1}^{\infty} q_1^{i-1}\left[9\left(1 - \mathrm{e}^{-2iT^*}\right) - 4\left(1 - \mathrm{e}^{-3iT^*}\right)\right]\right\} + \sum_{i=1}^{\infty} q_1^{i-1}\left(3\mathrm{e}^{-2iT^*} - 2\mathrm{e}^{-3iT^*}\right) = \frac{\alpha_1}{\alpha_1(1 - q_1) - \alpha_2 q_3 - \alpha_3 q_2} \tag{10}$$

This means that equation (10) is the condition for the existence of the optimal solution T^* of model (9).

To solve for the optimal solution T^* from Equation (10), it is necessary to give the values of three maintenance probabilities.

4.2 Probability of Imperfect Maintenance and Perfect Maintenance

To determine appropriate values for imperfect repair probability q_1 and perfect repair probability q_2, we initially establish a system of artificial factor indicators that lead to different repair effects, as shown in Figure 2 (Appendix).

We invite civil aviation experts to score the impact of human factors on maintenance effectiveness in Figure 2 (Appendix), and evaluate the importance of human factors based on the analytic hierarchy process, [15], [16], [17].

The calculation formulas for the maximum eigenvalue λ_{max}, consistency index CI, and consistency ratio CR are provided below. In the subsequent text, only the solution results will be presented without repeating the formulas.

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{[A\omega]_i}{n\omega_i}$$

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

Table 1 presents the table of random consistency index (*RI*) values.

Table 1. Random Consistency Index (*RI*) Values

matrix coefficient	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

Source: created by the authors

Matrix A is a 3rd-order judgment matrix, and the random consistency index (*RI*) value can be found from Table 1 as 0.52.

The normalized eigenvector and eigenvalue of Matrix A are calculated, and the consistency test is conducted. The results are shown in Table 2 and Table 3.

Table 2. Matrix A and Its Normalized Eigenvector and Eigenvalue

A	B1	B2	B3	Eigenvalue	Normalized Eigenvector
B1	1.000	3.000	3.000	1.8	0.6
B2	0.333	1.000	1.000	0.6	0.2
B3	0.333	1.000	1.000	0.6	0.2

Source: created by the authors

Table 3. Summary of Consistency Test Results for Matrix A

maximum eigenvalue	*CI*	*RI*	*CR*	Results of consistency test
3.000	0.000	0.520	0.000	Pass

Source: created by the authors

For the "Technology" dimension, its matrix is a 2nd-order judgment matrix; for both the "Personnel" and "Environment" dimensions, their matrices are 3rd-order judgment matrices. By repeating the above operations in sequence, the results shown in Table 4, Table 5, Table 6, Table 7, Table 8 and Table 9 can be obtained.

Table 4. Matrix B1 and Its Normalized Eigenvector and Eigenvalue

B1	C1	C2	C3	Eigenvalue	Normalized Eigenvector
C1	1.000	2.000	1.000	1.2	0.4
C2	0.500	1.000	0.500	0.6	0.2
C3	1.000	2.000	1.000	1.2	0.4

Source: created by the authors

Table 5. Summary of Consistency Test Results for Matrix B1

maximum eigenvalue	*CI*	*RI*	*CR*	Results of consistency test
3.000	0.000	0.520	0.000	Pass

Source: created by the authors

Table 6. Matrix B2 and Its Normalized Eigenvector and Eigenvalue

B2	C4	C5	Eigenvalue	Normalized Eigenvector
C4	1.000	3.000	1.5	0.75
C5	0.333	1.000	0.5	0.25

Source: created by the authors

Table 7. Summary of Consistency Test Results for Matrix B2

maximum eigenvalue	*CI*	*RI*	*CR*	Results of consistency test
2.000	0.000	0.000	Null	Pass

Source: created by the authors

Table 8. Matrix B3 and Its Normalized Eigenvector and Eigenvalue

B3	C6	C7	C8	Eigenvalue	Normalized Eigenvector
C6	1.000	2.000	2.000	1.500	0.50
C7	0.500	1.000	1.000	0.750	0.25
C8	0.500	1.000	1.000	0.750	0.25

Source: created by the authors

Table 9. Summary of Consistency Test Results for Matrix B3

maximum eigenvalue	*CI*	*RI*	*CR*	Results of consistency test
3.000	0.000	0.520	0.000	Pass

Source: created by the authors

The total weights calculated as shown in Table 10 (Appendix) serve as the importance degree of C with respect to A.

Assuming there are four types of maintenance personnel, their human factor levels are scored on a five-point scale, denoted as S_{ij} (i=1,2,...,8; j=1,2,3,4). A higher S_{ij} score indicates a higher human factor level for the *i*-th factor of the *j*-th type of maintenance personnel. The results are shown in rows 3 through 11 of Table 11 (Appendix).

The formula for calculating the total human factors score for each maintenance personnel category is presented as follows. $S_j=\sum_{i=1}^{i=8} s_{ij} * \omega_i$

The results are presented in row 12 of Table 11 (Appendix).

For Table 12, based on the total score ranges for different factor levels, a four-category classification is performed, reflecting varying levels. The values for q_1, q_2, and q_3 are determined based on practical experience.

Table 12. total score ranges, q_1, q_2, and q_3 of a four-category classification

Category	S_j	q_1	q_2	$q_3=1-q_1-q_2$
Senior Expert Type	[0,2]	0.05	0.65	0.3
Team Cooperation Type	(2,3]	0.10	0.70	0.2
Technological Innovation Type	(3,4]	0.15	0.75	0.1
Young and Growing Type	(4,5]	0.20	0.80	0

Source: created by the authors

4.3 Parameter Sensitivity Analysis

Given α_2/α_1= 0.1 and α_3=5 (h), they correspond to the situation in Table 11 (Appendix), respectively, and the results of optimal preventive maintenance time T^* ($\times 10^2$) are shown in Table 13.

Table 13. Optimal preventive maintenance time T^* ($\times 10^2$) for different q_2 and q_1 when α_2/α_1= 0.1 and α_3=5 (h)

α_2/α_1= 0.1 under the optimal maintenance cycle T^* ($\times 10^2$)				
q_1	q_2			
	0.65	0.70	0.75	0.80
0.05	0.20	0.19	0.18	0.18
0.10	0.18	0.18	0.17	0.16
0.15	0.17	0.16	0.16	0.15
0.20	0.16	0.15	0.14	0.14

Source: created by the authors

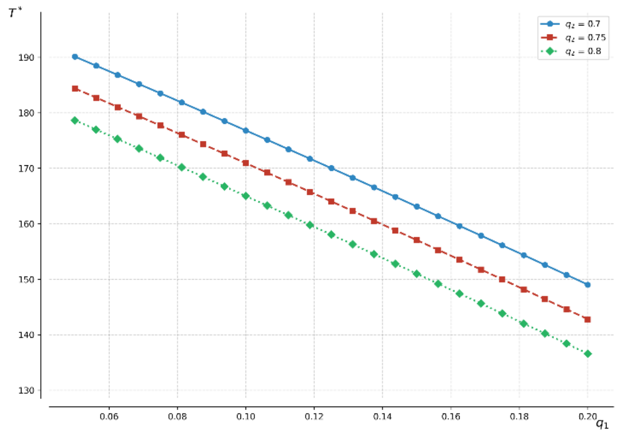

Fig. 3: The variation trend of T^* with q_1 under different q_2

Source: created by the authors

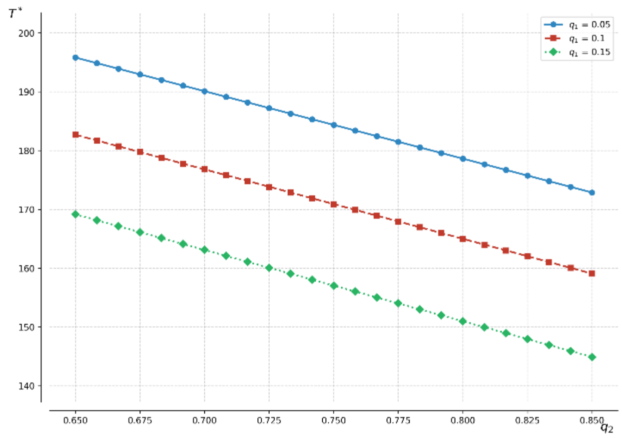

Fig. 4: The variation trend of T^* with q_2 under different q_1

Source: created by the authors

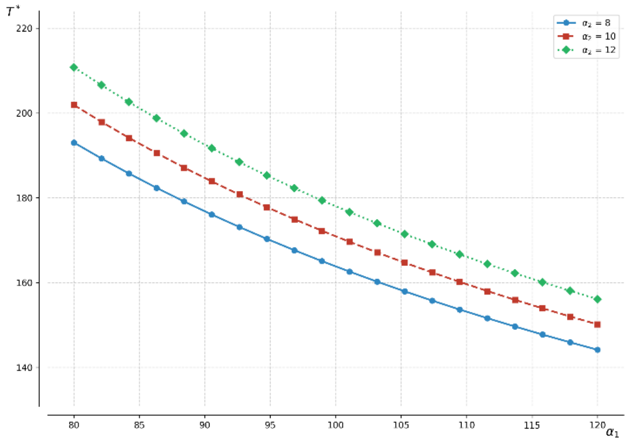

Fig. 5: The variation trend of T^* with α_1 under different α_2

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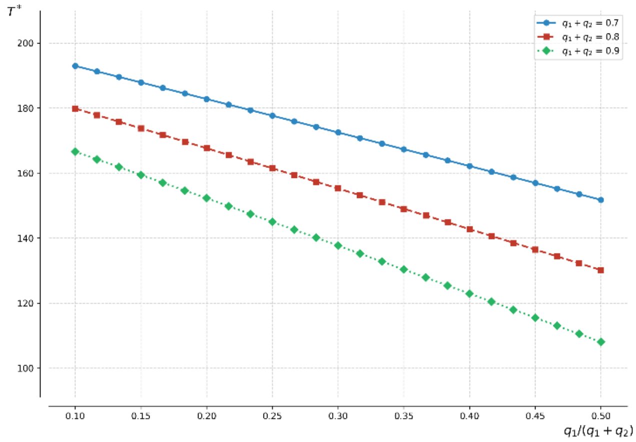

Fig. 8: The variation trend of T^* with $q_1/(q_1+q_2)$ under different (q_1+q_2)

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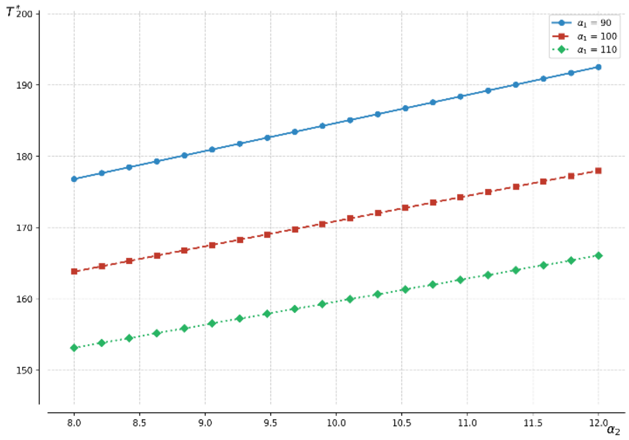

Fig. 6: The variation trend of T^* with α_2 under different α_1

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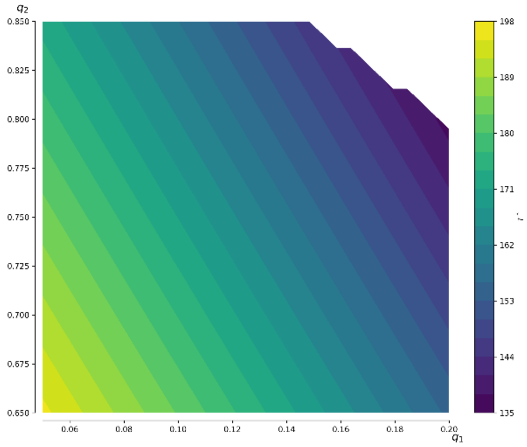

Fig. 9: Joint sensitivity thermal map of q_1 and q_2

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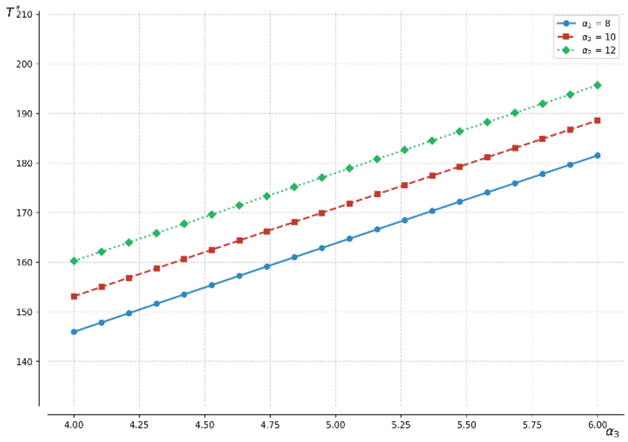

Fig. 7: The variation trend of T* with α_3 under different α_2

Source: created by the authors

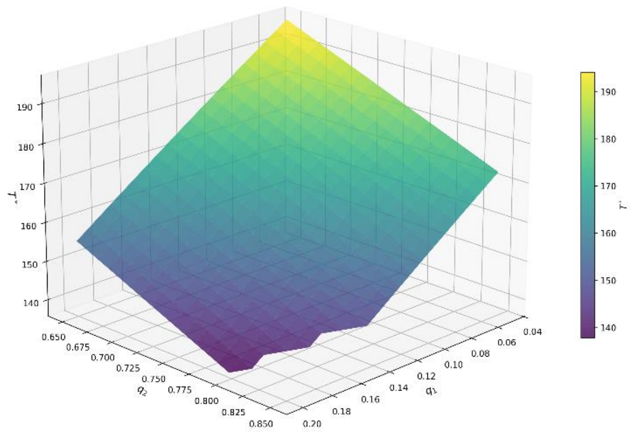

Fig. 10: 3D surface view of q_1 and q_2, T^*

Source: created by the authors

After Python programming calculation, it is obtained that when the average fault-free time of each unit is 104 hours, the optimal preventive maintenance time T^* is 164.026 hours, that is to say, the system should be maintained every 6.8 days or once a week.

The results obtained by sensitivity analysis are shown in Figure 3, Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8. The analysis is as follows:

Figure 3 shows that with the increase of q_1 (0.06-0.20), the optimal T^* continues to decrease. The trend is consistent under different q_2 values (0.70,0.75,0.80), and the smaller the q_2 value, the larger the corresponding T^* is for q_1. This indicates that the higher the probability of imperfect maintenance, the shorter the system maintenance cycle needs to be.

Figure 4 shows that when q_2 increases (0.65-0.85), the optimal T^* decreases significantly. Different q_1 values (0.05,0.10, 0.15) all follow this rule, and the larger q_1 is, the smaller T^* corresponding to q_2 is. This indicates that the improvement of perfect maintenance probability can shorten the optimal maintenance cycle.

Figure 5 shows that the optimal T^* decreases continuously with the increase of α_1 (80-120 hours). The trend is consistent under different α_2 values (8,10,12), and the larger the α_2, the higher the T^* corresponding to α_1. It indicates that the longer the actual maintenance time, the shorter the maintenance cycle needs to be.

Figure 6 shows that the optimal T^* increases significantly with the increase of α_2 (8-12 hours). Different α_1 values (90,100,110) all follow this rule, and the larger the α_1, the lower the corresponding T^* is. This indicates that the longer the preventive maintenance failure repair time, the longer the maintenance cycle needs to be extended.

Figure 7 shows that the optimal T^* continues to rise with the increase of α_3 (4-6 hours). The trend is consistent under different α_2 values (8,10,12), and the higher the α_2, the higher the T^* corresponding to α_3. It indicates that the longer the perfect repair time is, the longer the maintenance cycle needs to be.

Figure 8 shows the change of the optimal maintenance interval T^* with $q_1/(q_1+q_2)$ under different (q_1+q_2), which represents the probability of imperfect maintenance in the total maintenance. It can be seen that $q_1/(q_1+q_2)$ has a significant effect on T^*, indicating that the uncertainty of maintenance type significantly affects the maintenance strategy. As the ratio increases, the T^* gradually decreases because the overall maintenance effect of the system becomes worse and more prone to failure due to the increase in the proportion of imperfect maintenance, so the maintenance interval needs to be shortened to maintain reliability. The results show that when imperfect maintenance is the main focus, the maintenance interval should be appropriately reduced to control the system risk.

Figure 9 and Figure 10 show the combined effects of heat maps and 3D surface maps analyzing the effects of q_1 and q_2, when q_1 is low and q_2 is high, T^* is the smallest, about 120 hours, and when q_1 is high and q_2 is low, T^* is maximum, about 200 hours; There is a clear interaction between q_1 and q_2: an increase in q_1 amplifies the effect of a decrease in q_2, and vice versa.

5 Conclusions

In this paper, we comprehensively consider the imperfect maintenance outcomes caused by human error, aiming to maximize availability. We establish a decision-making model for optimizing preventive maintenance timing and design corresponding algorithms to solve the model. The effectiveness of the model and algorithm is verified through case studies. Finally, sensitivity analysis shows that different distribution parameters and reliability levels of individual aircraft components significantly impact the optimal strategy. Our future research will extend to multi-component system maintenance optimization, exploring collaborative maintenance strategies under component failure correlations and resource constraints, and developing intelligent algorithms to enhance maintenance efficiency and system reliability.

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APPENDIX

Table 10. Importance of Human Factors on Maintenance Effectiveness

Number (i)	1	2	3	4	5	6	7	8
Human Factors (Ci)	Professional Knowledge (C1)	Training Intensity (C2)	Maintenance Experience (C3)	Maintenance Level (C4)	Operational Capability (C5)	Humanistic Environment (C6)	Economic Environment (C7)	Social Environment (C8)
Weight (ω_i)	24%	12%	24%	15%	5%	10%	5%	5%

Source: created by the authors

Table 11. Human Factors Scores and Imperfect Repair Probabilities for Four Maintenance Personnel Categories

Human Factors	Scores(S_{ij})			
	Personnel Type 1	Personnel Type 2	Personnel Type 3	Personnel Type 4
Professional Knowledge (C1)	5	4	3	2
Training Intensity (C2)	4	3	3	2
Maintenance Experience (C3)	5	3	2	1
Maintenance Level (C4)	5	3	4	1
Operational Capability (C5)	5	4	3	1
Humanistic Environment (C6)	5	5	3	2
Economic Environment (C7)	4	4	3	1
Social Environment (C8)	4	4	2	1
Total Score for Factor Level (S_j)	4.78	3.59	2.86	1.46
Imperfect Maintenance Probability (q_1)	0.20	0.15	0.10	0.05
Perfect Maintenance Probability (q_2)	0.80	0.75	0.70	0.65
Failed Maintenance Probability (q_3=1-q_1-q_2)	0	0.10	0.20	0.30

Source: created by the authors

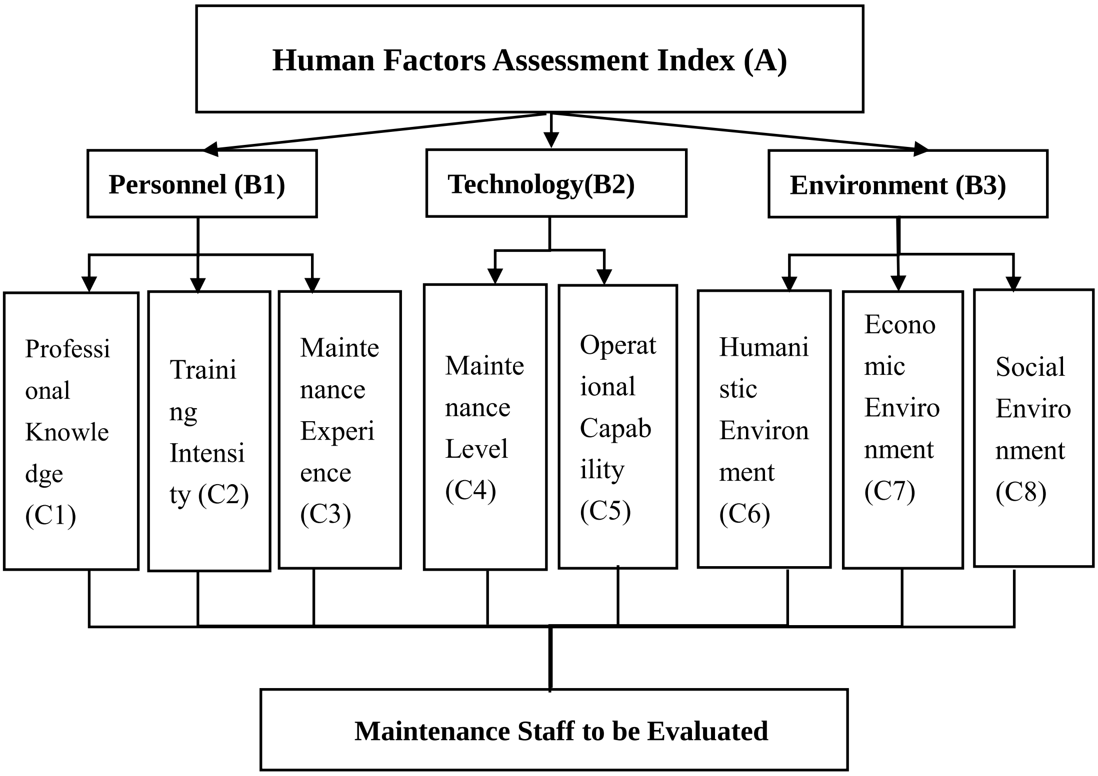

Fig. 2: Human factor evaluation system

Source: created by the authors

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Kaiting Wen and Chunxiao Zhang carried out model construction and algorithm design.
- Ziying Guo implemented and debugged the computational algorithms in Python.
- Jingwen Tan performed case study analysis and experimental validation.
- Xuefei Jia was responsible for the human error probability modeling and analysis.
- Tongtong Zhao executed a sensitivity analysis with a parametric investigation.
- Xiang Li conducted a literature review and data collection.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent

Informed consent was obtained from all individual participants included in the study.