

# Research on Comprehensive Evaluation Model for Aeroengine Alternative Schemes Based on Multi-Source Data Fusion

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**Abstract:** During the demonstration phase of the aeroengine alternative schemes, the evaluation of alternative schemes plays a critical role in determining the most viable options. However, the complexity and diversity of evaluation factors pose challenges to traditional evaluation methods. To tackle this issue, integrating pertinent data from diverse sources is imperative for analysis to identify the optimal scheme. A comprehensive evaluation model combining fuzzy mathematics theory and analytic hierarchy process (AHP) has been established to integrate quantitative and qualitative factors. Firstly, a comprehensive evaluation index system for aeroengines in the demonstration stage is established. Secondly, utilizing fuzzy mathematics theory, the unified processing of quantitative and qualitative indicators from multiple data sources is completed. Thirdly, employing the Analytic Hierarchy Process (AHP), weight coefficients of evaluation indicators at each level are determined. Finally, the weighted sum of each indicator is calculated step by step to derive the comprehensive evaluation results for each alternative scheme. A case study is conducted to demonstrate the effectiveness of the proposed model in evaluating aeroengine alternative schemes. By comparing the evaluation results with the PUGH matrix method, it is demonstrated that this comprehensive evaluation model is not only reasonable and feasible but also possesses higher credibility. The model established for alternative schemes in this study serves as a crucial foundation for the scientific selection of the optimal scheme in the demonstration stage.

**Key words:** aeroengine; Analytic Hierarchy Process; fuzzy mathematics theory; comprehensive evaluation model

## 1 Introduction

The aeroengine represents a highly interlinked "fluid-solid-thermal" complex fluid mechanical thermodynamic system. The comprehensive evaluation of alternative options encompasses a multitude of dimensions. To determine the optimal scheme, it is essential to efficiently integrate information gathered from various sources and carry out unified processing and analysis. Hence, a scientifically sound comprehensive evaluation model plays a vital role in decision-making for alternative options. This model must effectively harmonize qualitative and quantitative evaluation indicators. Moreover, the methodology used to assign weights to these indicators should be logical and efficient, mitigating the subjectivity inherent in straightforward comparisons.

The Analytic Hierarchy Process (AHP), a decision-making method that integrates qualitative and quantitative criteria, finds extensive application in engineering. Donald et al.<sup>[1]</sup> developed a three-level comprehensive evaluation model for aeroengines using AHP. Liu et al.<sup>[2]</sup> employed the triangular fuzzy AHP method to calculate weights for power equipment demand indicators in ships, effectively addressing ambiguity issues in obtaining these indicators. Liu<sup>[3]</sup> formulated a comprehensive evaluation model for ship propulsion

systems using AHP, offering scientific insights for the management and upkeep of ship propulsion systems. Luo et al. [4] implemented AHP to devise a technical status assessment approach for ship power systems, laying the groundwork for proficiently assessing indicators and interconnections across different levels. Yuan et al. [5] leveraged AHP to devise strategies for steady-state performance debugging of aeroengines, enhancing the methodology for optimizing the overall performance of turbofan engines. Yang et al. [6] devised a multi-dimensional risk evaluation model for aeroengine systems utilizing AHP, offering a theoretical foundation for the evolution of engine delivery modes. Zhang et al. [7] conducted a quantitative analysis of civilian engine option optimization through AHP. Wang et al. [8] hierarchically decomposed the selection criteria for civil aeroengines and developed a comprehensive evaluation system and selection assessment method using AHP. These studies have made valuable efforts in addressing complex engineering challenges using AHP and have affirmed its rationality in analyzing indicator weights. However, there remains a dearth of research on the application of AHP in the decision-making process involving multiple engine options with data fusion, and few research findings have been reported in this specific domain.

The article centers on the necessity of integrating diverse data sources during the validation phase of aeroengine design proposals. It tackles the challenge of harmonizing qualitative and quantitative criteria by leveraging fuzzy theory and establishes a hierarchical evaluation system for alternative proposals using the Analytic Hierarchy Process (AHP). Expanding on this framework, a comprehensive evaluation model is formulated, integrating quantitative, semi-quantitative, and qualitative factors to effectively harness information from various sources for multidimensional evaluations of alternative proposals. The primary objective is to furnish a crucial foundation for scientifically determining the optimal proposal during the validation phase.

## 2 System Formulation and analysis methodology

### 2.1 Integrated Evaluation Index System

There are numerous indicators that characterize aeroengines, sourced from various methods of evaluation [9-11]. For instance, when considering turbofan engines for fighter planes, critical evaluation indicators during the design phase can be broadly categorized into three groups.

#### (1) Combat Performance Indicators

Through an analysis of fighter combat scenarios, key combat performance indicators that delineate the technical capabilities of its powerplant encompass: thrust indicators facilitating increased payload and enhanced penetration capabilities, fuel consumption indicators enabling extended combat radius and prolonged loiter time, stealth and thermal management indicators bolstering survivability, and overall aircraft weight optimizing maneuverability during combat operations [9].

Enhancements in these indicators consistently and continuously play a pivotal role in augmenting the combat capabilities of fighters. Consequently, to realize the intended design proposals, a preference is given to higher values of these indicators.

#### (2) Constraint Indicators

As the primary power source, the engine must "match" the aircraft to function effectively. Regarding physical dimensions, external measurements such as length must align with the installation requirements within the aircraft [11-13]. For optimal performance, the operational range of the engine must align with the platform's operating capabilities. If the engine's envelope is too limited, the aircraft may not fully achieve its operational potential. Conversely, an excessively large operational envelope that surpasses the aircraft's design parameters

would also be impractical.

It must be noted that these indicators are intricately linked to the aircraft design proposal. In the design phase, it is essential to adhere to the specified constraints of the aircraft and allow for a certain margin, rather than striving for continuous improvement of the indicators.

### (3) Feasibility Indicators

In the phase of justifying the design proposal, numerous indicators that are vital for proposal selection cannot be quantitatively assessed. These are classified as "feasibility indicators." The evaluation indicators outlined in this document encompass development potential <sup>[14]</sup>, development cost, technological maturity, and technological inheritability.

While these indicators may be challenging to quantify entirely, qualitative assessments and relative rankings can be established through engineering expertise during the evaluation of design proposals. The overarching principle is that higher values of these indicators signify better performance.

## 2.2 Multi-source Data Fuzzy Evaluation Method

Among the indicators outlined in section 2.1, certain factors rely on engineering experience, making them challenging to quantitatively assess during the design proposal justification phase. Moreover, certain quantitative indicators exhibit minimal variations across diverse proposals. When these are assessed on a standardized scale, even slight variances could significantly influence decision-making outcomes. To tackle these challenges, fuzzy mathematics theory is introduced to harmonize the processing of data from multiple sources.

The primary objective when applying fuzzy theory to address problems is to define membership functions. This paper adopts the commonly utilized trapezoidal distribution in engineering to establish membership functions for grading indicators, as illustrated in Figure 1. This transformation categorizes multiple data sources into four levels {Excellent, Good, Qualified, Unqualified}, corresponding to quantitative scores of {3, 2, 1, 0}. The function depicted in Figure 1(a) is suitable for indicators that aim for lower values, such as fuel consumption performance, stealth performance, and overall aircraft weight, while the function in Figure 1(b) is appropriate for indicators that target higher values, including thrust performance, thermal management performance, etc.

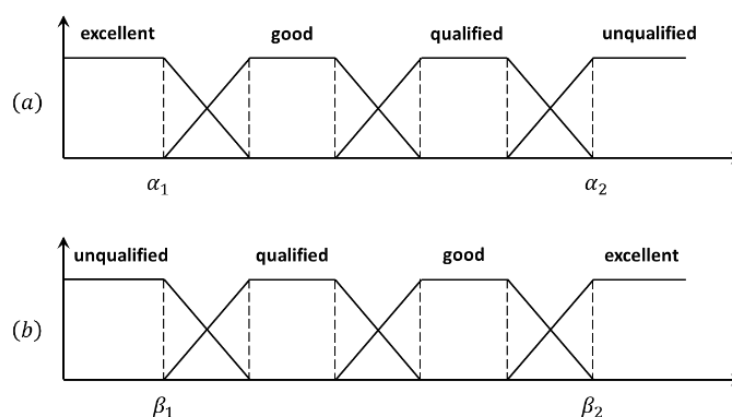


Fig. 1 Indicator Grading Membership Function Based on Trapezoidal Distribution

Regarding a particular underlying indicator, the unified treatment method based on fuzzy theory is outlined as follows:

Step 1: Engage in thorough discussions among the project evaluation experts to define the grading membership functions.

Step 2: Utilize the standardized grading membership functions to derive the indicator's fuzzy evaluation grade vector  $\mu = \{\mu_1, \mu_2, \mu_3, \mu_4\}$ .

Step 3: Utilize the standardized quantitative rating levels to finalize the quantitative evaluation of the indicator with  $p = \mu \cdot (3, 2, 1, 0)^T$ .

### 2.3 Multi-level Indicator Weight Calculation Method

The Analytic Hierarchy Process (AHP) is a valuable method for handling intricate multi-criteria decision-making problems, producing weight coefficients for different levels of indicators based on comprehensive expert evaluations. The primary steps of the AHP comprise:

#### (1) Establishing a Hierarchical Structure Model

Constructing a hierarchical structure model grounded in the physical problem is crucial for applying the Analytic Hierarchy Process to tackle complex challenges. As illustrated in Figure 2, when evaluating alternative aviation engine schemes comprehensively, the initial stage is the goal level, aimed at identifying the optimal scheme. Subsequently, a second-level criteria layer is formed based on the comprehensive evaluation indicator system detailed in section 2.1. Lastly, the scheme layer is established, encompassing numerous potential alternative schemes.

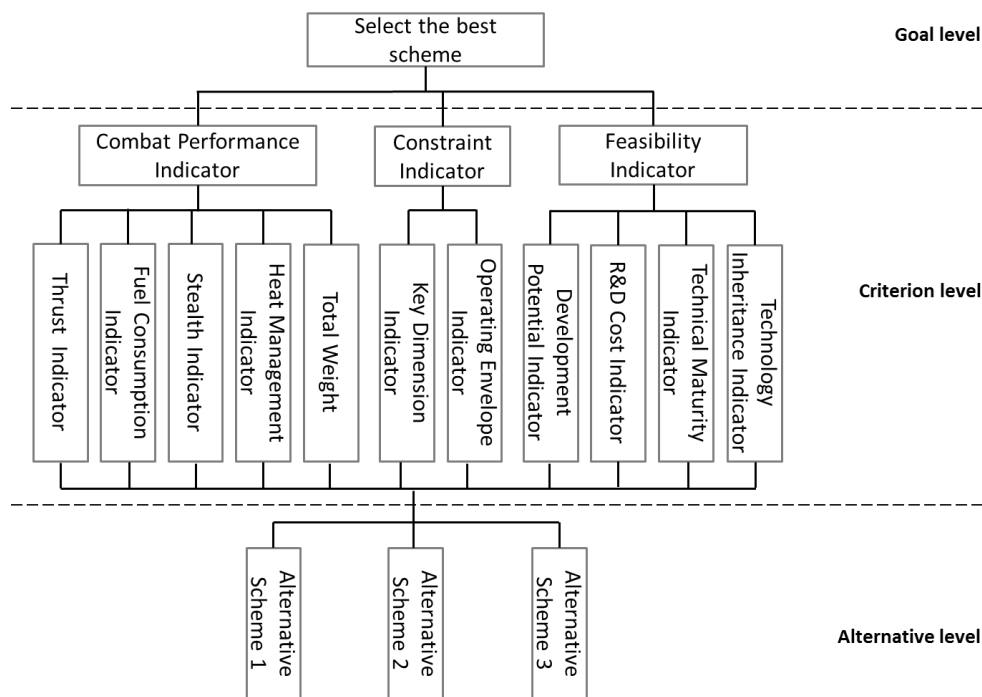


Fig. 2 Optimal Model for Alternative Aviation Engine Schemes

#### (2) Constructing the judgment matrix

Once the hierarchical structure model is established, each indicator possesses a distinct hierarchical relationship. Assuming that  $A_1, A_2, \dots, A_n$  belong to the criterion A, the relative importance between  $A_1, A_2, \dots, A_n$  can be quantified using pairwise comparisons and comparison scales. The relative importance of  $A_i$  to  $A_j$  is denoted by  $a_{ij}$ , and its value is measured using Saaty's 1-9 scale method [15], as shown in Table 1. Thus, a comparison matrix  $R$  can be constructed, with its expression as shown in Equation (1).

Table 1 Comparative Scale Values

标度	含义
1	indicates that two indicators are equally important compared to each other
3	indicates that one indicator is moderate importance compared to each other
5	indicates that one indicator is strong importance compared to each other
7	indicates that one indicator is very strong importance compared to each other
9	indicates that one indicator is extreme importance compared to each other
2、4、6、8	values between these integers can also be used to represent intermediate levels of importance
reciprocal	If the comparison of criterion $i$ to criterion $j$ is $a_{ij}$ , then the comparison of criterion $j$ to criterion $i$ is $a_{ji}=1/a_{ij}$ .

$$R = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

### (3) Calculation of Indicator Weights and Consistency Check

The foundation of constructing the judgment matrix is expert evaluation, and the results are influenced by subjective factors such as the knowledge and experience of the evaluators. This may lead to significant deviations in the resulting weight vector. Therefore, a consistency check is introduced to assess the reliability of the weight vector. The steps of the consistency check are as follows:

a) Calculate the consistency check index  $CI$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

where  $\lambda_{\max}$  is the maximum eigenvalue of the judgment matrix, and  $n$  is the order of the judgment matrix.

b) Calculate the average random consistency index  $RI$ , as well as the consistency ratio  $CR$

$$CR = \frac{CI}{RI} \quad (3)$$

where  $RI$  is the average random consistency index, as shown in Table 2, which is related to the order of the matrix. Generally, the higher the order of the judgment matrix, the greater the likelihood of random deviations occurring. When  $CR < 0.1$ , it is considered that the judgment matrix passes the consistency check; otherwise, the judgment matrix needs to be reconstructed. At this point, the normalized eigenvector becomes the weight vector. In cases where multiple experts are involved in the evaluation, the final weights can be determined using the arithmetic mean method.

Table 2 Average Random Consistency Index

order	2	3	4	5	6	7	8
$RI$	0	0.58	0.90	1.12	1.24	1.32	1.41

## 2.4 Multi-dimensional Comprehensive Evaluation Model

The process of multi-scheme optimization in the demonstration stage is shown in Figure 3. Starting from the preliminary selection of various alternative schemes, this study conducts final scheme research, as indicated by the dashed box in the figure. Firstly, the comprehensive evaluation index system for the scheme stage is established. Then, fuzzy mathematics theory is applied to unify the processing of multi-source data.

Subsequently, the Analytic Hierarchy Process (AHP) is used to analyze the weights of indicators at each level. Finally, by summing the weighted values at each level, the comprehensive evaluation and ranking of each alternative scheme are output.

The establishment of the aviation engine scheme comprehensive evaluation model based on fuzzy theory and AHP (referred to as the FT-AHP model) provides an important basis for scientific decision-making on the optimal scheme during the scheme demonstration stage.

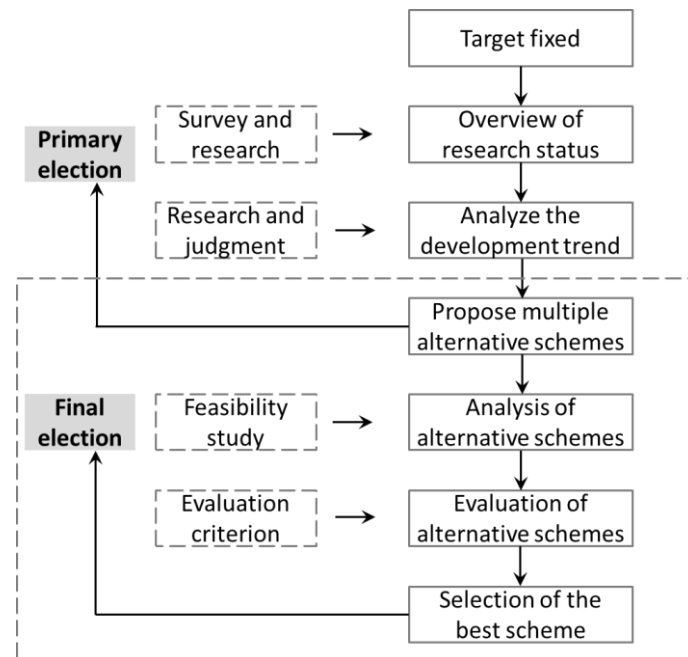


Fig. 3 Comprehensive Evaluation Process for Aviation Engine Schemes

### 3 Case Study

In this chapter, a case analysis of alternative options for a military turbofan engine project is constructed to demonstrate the specific application of the FT-AHP model established in this paper. On one hand, the usage process and technical details of the model are demonstrated and explained; on the other hand, the effectiveness of the model is verified by comparing the evaluation results with the PUGH method. The case includes 3 alternative options at the scheme level, with the participation of 4 experts in the evaluation. The comprehensive evaluation model established in this paper is also applicable to situations with more alternative options and evaluation experts.

#### 3.1 Unified Processing of Multi-Source Data

Following the principles of fuzzy mathematics, the underlying data of the 3 alternative options are uniformly processed. Without loss of generality, quantitative evaluation indicators and qualitative evaluation indicators are demonstrated using thrust and development potential as examples.

After thorough discussions, the 4 experts involved in the project evaluation defined that a supercruise thrust greater than 6000kgf is excellent, while less than 5000kgf is unacceptable, forming a fuzzy distribution grading membership function as shown in Figure 4. The fuzzy level vectors of the 3 alternative options are (0,0,1,0), (0.5,0.5,0,0), and (1,0,0,0) respectively. Therefore, the processing result for the thrust indicator is shown in Equation (4).

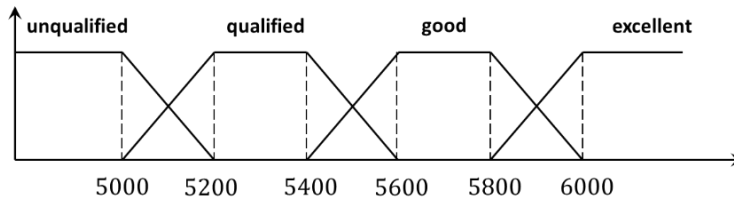


Fig. 4 Fuzzy Distribution Grading Membership Function for Thrust Indicator

$$\begin{bmatrix} C_{11} \\ C_{12} \\ C_{13} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 3 \\ 2 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 2.5 \\ 3 \end{bmatrix} \quad (4)$$

For the development potential indicator, qualitative evaluations can be conducted based on indicators such as innovation, application of advanced technologies, and scalability of the schemes, which are difficult to quantify directly. Therefore,

The first step involves quantifying the development potential indicators of each option through pairwise comparison matrices, where the quantified indicator is the arithmetic average of the evaluations by the 4 experts, specifically (0.30, 0.425, 0.275).

In the second step, the experts involved in the project evaluation collectively develop fuzzy distribution grading membership functions, as shown in Figure 5.

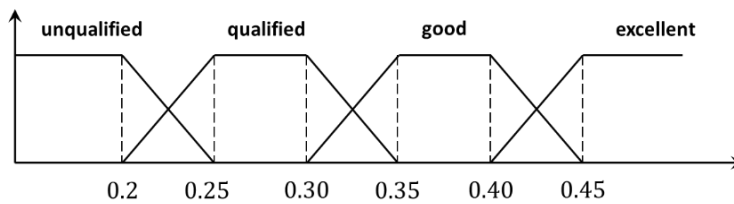


Fig. 5 Fuzzy Distribution Grading Membership Function for Development Potential Indicator

The third step involves determining the fuzzy level vectors of the development potential indicators for the 3 alternative options based on the grading membership functions.

The fourth step calculates the unified processing results for the development potential indicators, as shown in Equation (5).

$$\begin{bmatrix} C_{81} \\ C_{82} \\ C_{83} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 3 \\ 2 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.5 \\ 2.5 \\ 1 \end{bmatrix} \quad (5)$$

Other indicators are processed using the same method based on their own attributes, and the processing results are shown in Table 3. In principle, there are contradictions in the implementation measures of some indicators. For example, conflicts exist between achieving high thrust and low fuel consumption rate indicators in the selection of cycle parameters, between high performance output and low delivery weight, and between strong stealth indicators and low delivery weight. These contradictions are evident from the processing results of the indicators in Table 3. Therefore, the selection of the best scheme is the result of a comprehensive balance of various indicators.

### 3.2 Comprehensive Evaluation

Section 3.1 completed the unified processing of multiple data sources for each alternative scheme, and this section carries out a comprehensive evaluation. Firstly, the Analytic Hierarchy Process (AHP) is used to determine the weight coefficients of evaluation indicators at each level. Without loss of generality, this section provides calculations for the weight values of first-level evaluation indicators only, as shown in Table 4 with judgment matrices from 4 experts. It can be seen that all the judgment matrices satisfy  $CR < 0.1$ . Therefore, all 4 judgment matrices pass the consistency test, and the resulting weight vectors can be used for subsequent evaluations.

Table 3 Analysis of the Fundamental Data for Alternative Schemes

Goal Level	Criterion Level		Alternative Level		
	Primary Evaluation Criteria	Secondary Evaluation Criteria	Alternative Scheme 1	Alternative Scheme 1	Alternative Scheme 1
Select the best scheme $A$	Combat Performance Indicator $B_1$	Thrust Indicator $C_1$	1	2.5	3
		Fuel Consumption Indicator $C_2$	0.5	3	1.5
		Stealth Indicator $C_3$	1	2.5	1.5
		Heat Management Indicator $C_4$	1.5	2.5	2
		Total Weight $C_5$	2	2	2.5
	Constraint Indicator $B_2$	Key Dimension Indicator $C_6$	1.5	2	2.5
		Operating Envelope Indicator $C_7$	1	2	2.5
	Feasibility Indicator $B_3$	Development Potential Indicator $C_8$	0.5	2.5	1
		R&D Cost Indicator $C_9$	2.5	2	1.5
		Technical Maturity Indicator $C_{10}$	3	2	2
		Technology Inheritance Indicator $C_{11}$	2.5	1.5	2

Table 4 Expert Judgment Matrix

	$A$	$B_1$	$B_2$	$B_3$	Weight coefficient	$\lambda_{max}$	$CI$	$RI$	$CR$
Expert 1	$B_1$	1	7	3	0.643	3.066	0.033	0.58	0.057
	$B_2$	1/7	1	1/5	0.074				
	$B_3$	1/3	5	1	0.283				
	$A$	$B_1$	$B_2$	$B_3$	Weight coefficient				
Expert 2	$B_1$	1	6	5	0.723	3.029	0.015	0.58	0.025
	$B_2$	1/6	1	1/2	0.103				
	$B_3$	1/5	2	1	0.174				
	$A$	$B_1$	$B_2$	$B_3$	Weight coefficient				
Expert 3	$B_1$	1	5	3	0.633	3.039	0.02	0.58	0.034
	$B_2$	1/5	1	1/3	0.106				
	$B_3$	1/3	3	1	0.261				
	$A$	$B_1$	$B_2$	$B_3$	Weight coefficient				
Expert 4	$B_1$	1	6	4	0.685	3.054	0.027	0.58	0.047
	$B_2$	1/6	1	1/3	0.093				
	$B_3$	1/4	3	1	0.221				
	$A$	$B_1$	$B_2$	$B_3$	Weight coefficient				

Using the arithmetic mean method for the weight vectors provided by the 4 experts, the weight values of each first-level evaluation indicator are obtained as {Combat Performance Indicator, Constraint Indicator, Feasibility Indicator} =  $\{B_1, B_2, B_3\} = \{0.671, 0.094, 0.235\}$ . Employing a similar approach, the weight values of each second-level evaluation indicator can be determined sequentially. Ultimately, the weight quantification of evaluation indicators at each level is completed, as illustrated in Table 5.

Table 5 Analysis Results of Weighting for Each Evaluation Criterion

Goal Level	Primary Evaluation Criteria	Weight coefficient $\omega$	Secondary Evaluation Criteria	Weight coefficient $\omega$
Select the best scheme <i>A</i>	Combat Performance Indicator $B_1$	0.671	Thrust Indicator $C_1$	0.225
			Fuel Consumption Indicator $C_2$	0.237
			Stealth Indicator $C_3$	0.217
			Heat Management Indicator $C_4$	0.125
			Total Weight $C_5$	0.196
	Constraint Indicator $B_2$	0.094	Key Dimension Indicator $C_6$	0.487
			Operating Envelope Indicator $C_7$	0.513
	Feasibility Indicator $B_3$	0.235	Development Potential Indicator $C_8$	0.261
			R&D Cost Indicator $C_9$	0.243
			Technical Maturity Indicator $C_{10}$	0.213
			Technology Inheritance Indicator $C_{11}$	0.283

By utilizing the integrated processing outcomes from various data sources for alternative proposals (Table 3), and performing weighted summation according to the weight coefficients (Table 5) at each level, the comprehensive evaluation results for each alternative scheme are obtained, as shown in Table 6.

Table 6 Comprehensive Evaluation Results for Each Alternative Scheme

	Combat Performance Indicator	Constraint Indicator	Feasibility Indicator	Comprehensive evaluation	Ranking
Alternative Scheme 1	1.141	1.244	2.083	1.371	3
Alternative Scheme 2	2.520	2.000	1.990	2.347	1
Alternative Scheme 3	2.096	2.500	1.617	2.022	2

### 3.3 Method Validation

For the case constructed in this chapter, a comprehensive evaluation method combining qualitative and quantitative aspects widely used in engineering, the PUGH matrix method [16-18], was selected to validate the rationality of the comprehensive evaluation model established in this paper. The evaluation results of the PUGH matrix method are shown in Table 7, where the data required for evaluation are provided by the same group of experts who participated in the previous evaluation. It can be seen that according to the comprehensive evaluation of the PUGH matrix method, alternative scheme 2 is the best choice, which is consistent with the conclusion based on the comprehensive evaluation model established in this paper.

It is worth noting that in the comprehensive evaluation results obtained using the PUGH matrix method, the difference in comprehensive scores between alternative scheme 1 and alternative scheme 2 is only approximately 3% of the total score, which diminishes the credibility of the conclusion. This could be attributed to the fact that the underlying data in the PUGH matrix method is measured on a unified scale based on

comparison with the reference scheme, potentially amplifying the impact of minor differences or weakening the impact of significant differences. The comprehensive evaluation model established in this paper utilizes fuzzy mathematics theory for the unified processing of underlying data, effectively circumventing the aforementioned issues.

Table 7 PUGH Matrix Evaluation Table for Each Scheme

Evaluation Criteria		Importance	Alternative Scheme 1	Alternative Scheme 2	Alternative Scheme 3
Combat Performance Indicator	Thrust Indicator	4	5	7	9
	Fuel Consumption Indicator	5	3	9	7
	Stealth Indicator	4	3	7	5
	Heat Management Indicator	2	3	9	5
	Total Weight	4	5	5	7
Constraint Indicator	Key Dimension Indicator	3	3	5	7
	Operating Envelope Indicator	3	3	5	7
Feasibility Indicator	Development Potential Indicator	3	1	7	3
	R&D Cost Indicator	3	7	5	3
	Technical Maturity Indicator	3	9	7	7
	Technology Inheritance Indicator	4	7	3	5
Total Score			170	238	230
Ranking			3	1	2

Note: Each indicator is measured on a scale of 1 to 9, where a score of 9 represents the highest performance for a particular scheme, and a score of 1 represents the lowest.

#### 4 Conclusion

During the aviation engine scheme demonstration phase, there arises a practical necessity to amalgamate relevant information acquired through diverse channels. By amalgamating fuzzy theory with the AHP method, a comprehensive evaluation model has been formulated, which assimilates quantitative, semi-quantitative, and qualitative aspects of schemes. This model serves as a crucial foundation for scientifically determining the optimal scheme.

(1) A method has been developed, based on fuzzy mathematics theory, to unify multiple data sources related to alternative schemes, effectively addressing the challenge of unified processing of qualitative and quantitative evaluations. This approach can rectify the issue of amplifying the impact of minor indicator differences or weakening the impact of significant indicator differences. Furthermore, a hierarchical evaluation system for alternative scheme indicators has been established based on the AHP, and the consistency of judgment matrices can ensure the effectiveness of weight coefficients. By progressively weighting and aggregating various indicators, the comprehensive evaluation results of each alternative scheme are derived, providing support for optimal scheme selection. This model can mitigate the subjectivity of expert decisions and enhance the scientific nature and credibility of the evaluation results.

(2) Through a case study analyzing alternative schemes for a military turbofan engine project, the FT-AHP model proposed in this paper has been implemented in practical scenarios. A comparison with evaluation results based on the PUGH matrix method, derived from the same group of expert evaluations, illustrates that the FT-

AHP model is rational, feasible, and adept at fully leveraging evaluation information from diverse dimensions. Consequently, it leads to enhanced credibility of the evaluation results.

(3) The comprehensive evaluation index system proposed in this paper is tailored to a turbofan engine for fighter plane. However, with appropriate adjustments to relevant settings, the FT-AHP model established in this paper is equally applicable to other types of aviation engines.

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