Engine Selection Based on Utility Theory

Ding Songbin *, *Wang Xiaoli*, *Wang Hongyu*

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P. R. China

(Received 18 March 2016; revised 20 July 2016; accepted 5 August 2016)

Abstract: Since an engine is seen as the "heart" of an airplane, the objective and scientific evaluation of it is significant to ensure normal operation of airlines. Aiming at the limitations of current studies on selecting engines, a quantitative comprehensive evaluation system of engine options was established and an optimization model based on the utility theory and analytic hierarchy process (AHP) was proposed. Considering the judgement of different customers on the balance between income and risk, the utility of each evaluation index was determined by utilizing the piecewise utility function. The AHP was used to analyze individual demands of customers. Finally, the optimal scheme was selected through calculating the weighted utility value. According to the actual needs of a domestic airline, the utility of three engine options was calculated. The results showed that the value of risk factor can be set to determine the selection scheme based on the degree of preferences (conservative type, neutral type or adventurous type).

Key words: air transportation; engine selection; utility theory; civil aircraft; personalized demands

CLC number: U8 **Document code**: A **Article ID**: 1005-1120(2016)06-0639-08

0 Introduction

When airlines are planning to purchase aircraft to meet the operational requirements of expanding routes, they have to determine the type of aircraft. Engine selection directly affects performance, economy, maintainability, adaptability of routes and environmental protection level indicators of a whole aircraft. Therefore, with the increasing demand of consumers, evaluations of comprehensive performances of different engines are becoming crucial, as the national regulations are getting stringent.

In recent years, considerable scholars and airlines conducted a series of studies on engine selection, which mainly focused on the reliability, maintainability, operation cost, economy and other aspects. Each of them only analyzed a single engine index, such as engine economical index analysis based on cash operating cost (COC) and engine reliability analysis[1], the economic analysis of engine based on developing production cost[2], the engine evaluation and selection method based on performance[3-4], the reliability and life cycle evaluation analysis of engines[5-6] and so on. Besides, the results of some studies were based on qualitative evaluation, instead of quantitative methods. The final evaluation results are thus not intuitionistic. Therefore, the utility theory together with the analytic hierarchy process (AHP) method is proposed in this paper to establish the engine selection effectiveness evaluation system and to conduct the quantitative evaluation.

Utility, using probability to reflect the uncertainty of the research problem, refers to the satisfaction degree of customer for particular services or resources and their function under the action of market orientation[7]. At present, utility theory has been widely used risk evaluation [8-9], consumption theory[10], resource scheduling[11], investment portfolio[12] and target selection[13], etc. When selecting engines, using the quantitative

* Corresponding author, E-mail address: dingzhili@nuaa.edu.cn.

How to cite this article: Ding Songbin, Wang Xiaoli, Wang Hongyu. Engine selection based on utility theory[J]. Trans. Nanjing Univ. Aero. Astro., 2016,33(6):639-646.

http://dx.doi.org/10.16356/j.1005-1120.2016.06.639

evaluation method based on utility function can help to obtain the orders of the alternative engines. At the same time, the results may reflect the preferences and goals of airlines on engine selection, and the differences among the demands of users. Therefore, a method of selecting a suitable engine model is provided, according to the requirements and application characteristics of a specific user. In addition, the utility function is combined with AHP to investigate the reliability, sustainable development, economical efficiency, competitiveness, the level of environmental protection and some other factors of engines. The impact of the development orientation of airlines is considered, which may help to provide quantitative evaluation results more scientifically and intuitively.

1 Engine Evaluation Index System

The scientific and quantitative selection of engines is crucial to normal operation of aircraft. The seletion should meet the requirements of reliability, economical efficiency, competitiveness, environmental protection level, sustainablty, ect. Accordingly, the first-level indicators and the secondary evaluation index system is constructed, as shown in Fig. 1.

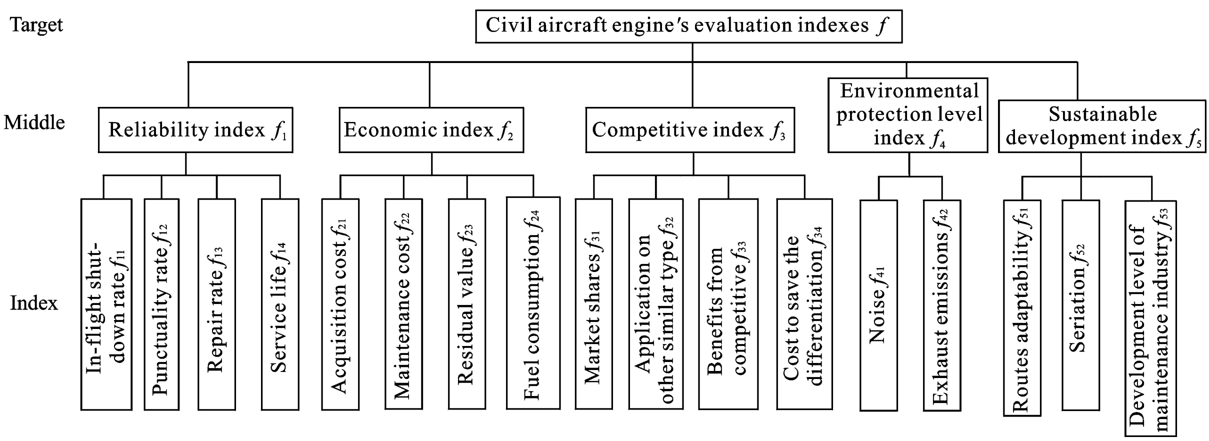

Fig. 1 The evaluation index system of civil aircraft engines

1.1 Reliability index

Reliability is one of the important indexes to measure the quality of aviation engines. It is also an important parameter to represent aircraft comprehensive efficiency. Engine reliability evaluation focuses on engine operating reliability and will indirectly affect the capacity and efficiency of the airlines. If it cannot meet the minimum requirements, it will become a negative factor. At present, according to Air Transport Association (ATA)[14], the most common maintainability and reliability parameters of civil aviation engines are: In-flight shut-down rate (IFSDR), indicating the number of engine parking in the air per one million hours of flight; Punctuality rate (PR), indicating the number of punctual opened flights per 100 flights, which equal to one minus the number of flight delay or cancellation due to engine reasons, repair rate (RR), indicating the number of engines sent back to factory for repair in every 1 000 h of flight, and so on. In addition, the service life of the aviation engine is one of the important characteristics of its competitiveness and durability, which inturn greatly affects the reliability and safety of the engine.

1.2 Economic index

At present, there are only a few international civil aviation engine manufacturers in the world. Through the long-term operation of the civil aviation aircraft, the reliability of their engines has been fully testified. In contrast, the economic performance of engine accounts for a large proportion of the entire aircraft cost, which is an important impact on the operating cost control of airlines. The economic assessment of engine includes acquisition cost (10 000 RMB), maintenance cost used in the process (10 000 RMB), engine residual value (10 000 RMB) and fuel consumption per flight hour.

1.3 Competitive index

There is a competitive relationship between different engine suppliers in the engine selection of a certain aircraft. Various factors, including market shares, applications to other similar models, sale strategies of suppliers, and differentiations of cost, cannot be ignored in the assessment of engine selection, because they are to bring revenue or cost to competition of suppliers.

1.4 Environmental protection level index

Aircraft are playing an increasingly important role in people's daily life. However, the adverse effects caused by the aircraft to the environment have become serious. The impact of tail gas on the environment is considerable. In addition, as the environmental standards are getting stringent, the aircraft take-off and landing engine noise also can not be negleted. DB can be used as the index parameters to measure noise pollution (the distance is 1—1.5 m from the sound source).

1.5 Sustainable development index

The average life cycle of an aircraft is almost 25 to 30 years. Thus, when purchasing aircraft, airlines need not only to consider short-term goal, but also to predict future demand. For example, the choice of the engine should route adaptive capacity to adapt to the development of new routes in the future, and forcast the seriation development to ensure the chosen engine to be stable and healthy, etc. Obviously, in case being eliminated in the future competition, the sustainable development of engine is also essential for engine selection.

2 Engine Selection Model Based On Utility Theory

Engine selection should be based on the specific needs of users. Therefore, the utility function is introduced to describe the heterogeneity of the needs of different users, and reflect preferences and goals of different airlines when purchasing an aircraft.

2.1 Utility theory

The utility theory provides the conditions for the consistency of the value of the decision makers and the utility function, which is the rational axiom[15]. As the cardinal utility is unique under the positive linear transformation[16], the total effect can be expressed as

$$\mu = \sum \omega_i U(f_i) = \omega_1 U(f_1) + \omega_2 U(f_2) + \cdots + \omega_n U(f_n) \tag{1}$$

where μ means the overall evaluation of the utility; $\omega_1, \omega_2, \cdots, \omega_n$ are the corresponding weights of evaluation indexes; $U(f_1), U(f_2), \cdots, U(f_n)$ the evaluation indexes of the corresponding utility.

Supposing that there are n alternative plans, the program set is $\boldsymbol{A} = [A_1, A_2, \cdots, A_n]^{\mathrm{T}}$. The greater the total utility value, the more excellent the program. That is, if $\mu(A_i) > \mu(A_j)$, $A_i \succ A_j$ (note "$\succ$" as better).

AHP is used to determine the weights of each utility evaluation index[17]. The index hierarchy is shown in Fig. 1.

2.2 Establishment of utility function

(1) Construction of utility matrix

Let n represent the number of alternative plans $\{A_1, A_2, \cdots, A_n\}$ and m represent the number of property indexes. Using a_{ij} to represent the j th indicator's value of the ith plan, the utility matrix can be written as

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{nm} \end{bmatrix} \tag{2}$$

The indexes are distinguished as deterministic indexes and uncertainty indexes. The deterministic index are represented as practical values, and the uncertainty indexes are represented as a five grade classification method in fuzzy mathematics, namely excellent, good, medium, poor and worse, which corresponds to 0.9, 0.7, 0.5, 0.3 and 0.1 in the utility function respectively.

(2) Pretreatment of evaluation indexes

Before using the utility function, the evaluation indexes need not only to be quantified, but also to be standardized (namely non-dimensional treatment). Quantitative indexes can be generally divided into four types: Cost (the smaller, the better), benefit (the bigger, the better), fixed (up to a fixed value for optimal) and interval (stable within a certain interval for optimal). In this paper, the engine evaluation index system can be divided into two types: Cost type and benefit type. Using the range transforming method for standardization, the expression is shown as

① Cost type

$$\chi_{ij}=\frac{(a_i^{\max}-a_{ij})}{(a_i^{\max}-a_i^{\min})}\qquad \chi_{ij}\in[0,1] \tag{3}$$

② Benefit type

$$\chi_{ij}=\frac{(a_{ij}-a_i^{\min})}{(a_i^{\max}-a_i^{\min})}\qquad \chi_{ij}\in[0,1] \tag{4}$$

where χ_{ij} is the standard value of the jth index value for the ith plan, $i=1, 2,\cdots,m$; a_{ij} the actual value of the jth index for the ith plan; $a_i^{\max}$ and $a_i^{\min}$ are the maximum and the minimum value of the indexes, respectively.

After the above normalization process, the function $U(a_{ij})$ expressing the relationship between U and a_{ij} has been transformed into the function $U(\chi_{ij})$, which expresses the relationship between U and χ_{ij}, $\chi_{ij}\subseteq[0,1]$.

(3) Determination of the utility value of all level evaluation indexes

Utility represents the relationship between the studied objects and the preferred values of users. So the first step is to establish the utility function to determine the utility value. As mentioned above, the utility function contains the value judgment of users. There are some differences among users with different needs and desires of product. Some of them are risk-preferred, while others are risk-averse. Therefore, the piecewise utility function model is chosen to calculate the utility value the different indexe

① Cost type

$$U(a_{ij})=\begin{cases}0 & a_{ij}\geqslant a_i^{\max}\\ \left[\dfrac{a_i^{\max}-a_{ij}}{a_i^{\max}-a_i^{\min}}\right]^k & a_i^{\min}<a_{ij}<a_i^{\max}\\ 1 & a_{ij}\leqslant a_i^{\min}\end{cases} \tag{5}$$

② Benefit type

$$U(a_{ij})=\begin{cases}0 & a_{ij}\leqslant a_i^{\min}\\ \left[\dfrac{a_{ij}-a_i^{\min}}{a_i^{\max}-a_i^{\min}}\right]^k & a_i^{\min}<a_{ij}<a_i^{\max}\\ 1 & a_{ij}\geqslant a_i^{\max}\end{cases} \tag{6}$$

where the maximum utility value is expressed as 1, and the minimum utility value is expressed as 0. If the first derivative result of $U(a_{ij})$ about k is existent, the defined utility function expression is feasible. The value′s range of k indicates the attitude towards risk of user. Therefore, the utility function curve is divided into 3 types: $k<1$ indicates the conservative type; $k=1$ indicates the neutral type and $k>1$ indicates the adventure type, as shown in Figs. 2,3.

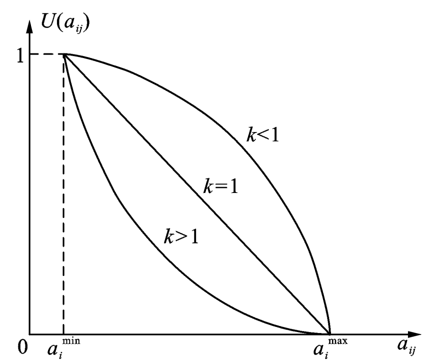

Fig. 2 Cost-type utility function curves

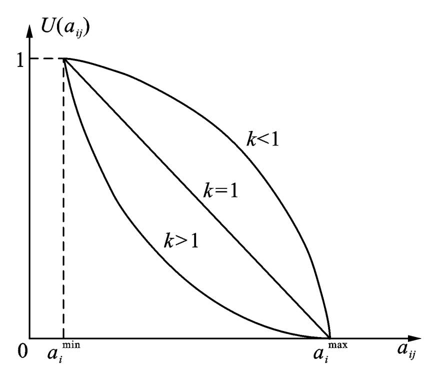

Fig. 3 Efficiency-type utility function curves

3 Application

3.1 Engine options

A domestic airline intends to introduce the A330-300 airplane. Airbus Company gives the selection manual which provides three engine options. The selection model based on utility theory is established as mentioned above to determine which option is most suitable for this airline.

Table 1 The specific parameters of the three kinds of engines for A330-300

Type	RR Trent 700	GE CF6-80E1	PW4000-100
IFSD rate / one million flight hours	0.692 9	0.703 3	0.7
Punctuality rate / 100 flights	99.90	99.95	99.97
Repair rate / 1 000 flight hours	0.031 0	0.033 3	0.020 0
Service life/a	29	26	28
Acquisition cost/10 000 RMB	4 066.128 0	4 251.550 0	4 371.087 6
Maintenance cost/10 000 RMB	5 084.660 0	5 314.437 5	5 253.859 5
Residual value/10 000 RMB	20.330 64	21.177 75	21.8554 38
Fuel consumption / one flight hour	10.230	9.945	10.010
Market share/%	56	7	32
Application on other similar type	Medium	Good	Excellent
Benefits from competition	Excellent	Medium	Good
Cost on saving the differentiation	Excellent	Medium	Good
Noise/dB	137	127	143
Exhaust emissions / 10^3 km	0.139 93	0.138 16	0.136 40
Route adaptability	Range covers all short and remote route	Range covers all short and remote route	Range covers all short and remote route
Seriation	3	5	3
Development level of maintenance industry	Excellent	Good	Good

These three engines are: Pratt & Whitney PW4000 series, General Electric CF6-80 series and Rolls Royce Trent of 700 series. According to the investigation, the specific parameters of the three engines are obtained and shown in Table 1.

3.2 Evaluation index system

As the evaluation index system given in Fig. 1 is too complicated to be used in practice, the indexes are not always considered together. Therefore, in order to simplify the model, according to Table 1, it can be found that these three engines are almost the same in routes adaptability, seriation, development level of maintenance industry and benefits from competition; the purchase cost and use cost of engine are proportionally related with each other; per flight hour exhaust emissions and per flight hour fuel consumption are positively correlated. In this case, the model will not consider the following six indexes: f_{21}, f_{33}, f_{42}, f_{51}, f_{52}, and f_{53}.

3.3 Weight vector of index system

According to the demand of a certain airline, the subjective and objective methods are combined to determine the weight of indexes. The comparison tables exhibiting the relative importance of the selected indexes are shown in Tables 2—6.

Table 2 Primary index importance comparison given by a certain airline

Index	f_1	f_2	f_3	f_4	f_5
f_1	1	1	3	1/3	1/5
f_2	5	1	8	2	1
f_3	1/3	1/8	1	1/5	1/8
f_4	3	1/2	5	1	1/2
f_5	5	1	8	2	1

Table 3 The secondary index importance comparison under reliability index

Index	f_{11}	f_{12}	f_{13}	f_{14}
f_{11}	1	1/3	1	2
f_{12}	3	1	3	3
f_{13}	1	1/3	1	3
f_{14}	1/2	1/3	1/3	1

Table 4 The secondary index importance comparison under economic index

Index	f_{21}	f_{22}	f_{23}	f_{24}
f_{21}	1	1/5	3	1/2
f_{22}	5	1	7	3
f_{23}	1/3	1/7	1	1/3
f_{24}	2	1/3	3	1

Table 5 The secondary index importance comparison under competitive index

Index	f_{31}	f_{32}	f_{33}	f_{34}
f_{31}	1	1/3	1/2	1
f_{32}	3	1	2	3
f_{33}	2	1/2	1	3
f_{34}	1	1/3	1/3	1

Table 6 The secondary index importance comparison under environmental protection level index

Index	f_{41}	f_{42}
f_{41}	1	1
f_{42}	1	1

According to the method of AHP, the weight vector of the first level indexes is given as: $\boldsymbol{\omega}_1 =$ [0.102 3, 0.339 1, 0.035 7, 0.183 8, 0.339 1]. The weight vector under reliability index of the secondary level indexes is given as: $\boldsymbol{\omega}_2 =$ [0.193 5, 0.488 3, 0.214 2, 0.104 0]. The weight vector under economic index of the secondary level indexes is given as: $\boldsymbol{\omega}_3 =$[0.134 9, 0.583 6, 0.064 7, 0.216 8]. The weight vector under competition index of the secondary level indexes is given as: $\boldsymbol{\omega}_4 =$[0.139 1, 0.448 5, 0.286 6, 0.125 7]. The weight vector under environmental protection level index of the secondary level indexes is given as: $\boldsymbol{\omega}_5 =$[0.5, 0.5].

Through the weighted multiplication of the weight of the first level indexes and secondary indexes above, the weight of the evaluation factors of civil aviation engines are calculated, so the index weight vector of A330-300 airplane′s engine evaluation of this airline is $\boldsymbol{\omega} =$ [0.019 8, 0.050 0, 0.021 9, 0.010 6, 0.197 9, 0.021 9, 0.073 5, 0.005 0,0.016 0, 0.004 5, 0.091 9].

3.4 Modeling based on the utility theory

Considering the effectiveness of the three engines of A330-300 with the 11 indexes f_{11}, f_{12}, f_{13}, f_{14}, f_{22}, f_{23}, f_{24}, f_{31}, f_{32}, f_{34}, f_{41}, the utility matrix $\boldsymbol{A}$ of the original data according to the Table 1 is constructed, and then the utility value matrix of the original data is obtained. Among them, f_{12}, f_{14}, f_{23}, f_{31}, f_{32} are benefit indexes, and f_{11}, f_{13}, f_{22}, f_{24}, f_{34}, f_{41} are cost indexes.

(1) Evaluation index pretreatment

According to Eqs. (3), (4), the parameters of the three engines of A330-300 are standardized. The results are shown in Table 7.

(2) Determination of the utility value of evaluation indicators at all levels

As the provided solutions of engines by aircraft manufactures are few in actual engine selections, this paper gives the acceptable interval of the index parameters (i.e., the user can accept all the parameters of the bottom line and the engine itself can achieve the optimal situation) to facilitate the application of the utility function, as shown in Table 8.

Substituting the numerical indexes in the matrix and $a^{\min}$, $a^{\max}$ in each known index into Eqs. (5), (6), the utility value of each index is obtained, and the utility matrix $\boldsymbol{U}$ can be constituted: $\boldsymbol{U} = [U(f_{11}), U(f_{12}), U(f_{13}), U(f_{14}), U(f_{22}), U(f_{23}), U(f_{24}), U(f_{31}), U(f_{32}), U(f_{34}), U(f_{41})]^{\mathrm{T}}$.

3.5 Scheme weighted utility value

When the values of k are different, the preference orders of the three schemes are also different. The results in different k values are shown in Table 9.

3.6 Analysis of results

(1) Analysis of evaluation index weight

According to the airlines evaluation index weight vector of A330-300, we can see that this company pays special attention on the maintenance cost of the engines, followed by the noise pollution problems of the engines, the fuel con sumption of engine and the airline operations flight punctuality rate.

Table 7 Standardized parameters

Type	f_{11}	f_{12}	f_{13}	f_{14}	f_{22}	f_{23}	f_{24}	f_{31}	f_{32}	f_{34}	f_{41}
RR Trent 700	0.380	0.816	0.580	0.833	0.815	0.689	0.385	0.560	0.286	0.143	0.433
GE CF6-80E1	0.363	0.918	0.534	0.333	0.586	0.745	0.528	0.070	0.571	0.714	0.767
PW 4000-100	0.368	0.959	0.800	0.667	0.636	0.790	0.495	0.320	0.857	0.429	0.233

Table 8 The acceptable range of each index parameters

Value	f_{11}	f_{12}	f_{13}	f_{14}	f_{22}	f_{23}	f_{24}	f_{31}	f_{32}	f_{34}	f_{41}
$a_i^{\min}$	0.300 0	99.50	0.01	24	4 900	10	9	0	0.3	0.3	120
$a_i^{\max}$	0.933 3	99.99	0.06	30	5 900	25	11	1	1.0	1.0	150

Table 9 The optimization results in different k values

k value	Total project utility value	Ranking	Optimal scheme
0.2	0.462 92, 0.464 88, 0.454 60	$A_2 > A_1 > A_3$	GE CF6-80E1
0.6	0.382 80, 0.385 27, 0.364 80	$A_2 > A_1 > A_3$	GE CF6-80E1
1	0.322 44, 0.322 47, 0.300 09	$A_2 > A_1 > A_3$	GE CF6-80E1
2	0.223 97, 0.214 24, 0.199 83	$A_1 > A_2 > A_3$	RR Trent 700
4	0.128 05, 0.108 16, 0.110 32	$A_1 > A_3 > A_2$	RR Trent 700
6	0.080 73, 0.063 69, 0.072 87	$A_1 > A_3 > A_2$	RR Trent 700

(2) Analysis of scheme utility value

As shown in Table 9, the differences among the utility values of the three engines are not significant, but there are still advantages and disadvantages. When $k<1$, $k=1$ (conservative and neutral type), GE CF6-80E1 has the maximum utility value. When $k>1$ (adventure type), RR Trent 700 has the maximum utility value.

In the airline's four most important indicators, the maintenance cost minimum utility value of RR Trent 700 is the highest, but the utility value of punctuality rate and fuel consumption per flight hour are both the lowest. So when the airline is adventuring and searching for lower input cost, RR Trent 700 is the best choice.

GE CF6-80E1 has the worst maintenance cost index utility but the best utility value of punctuality rate and noise index. In addition, the in-flight shutdown rate and repair rate of GE CF6-80E1 are also the lowest, so when airlines are in conservative and neutral type, considering company operation and social benefit, GE CF6-80E1 is the best choice.

(3) Analysis of k value selection

At present, the development of manufacturer or the use of airline aspects of the Rolls Royce RR Trent 700, GE's CF6-80E1 and Pratt & Whitney PW4000-100 both have been in a mature and stable stage. The airlines tend to care more about its operational efficiency. In addition, China has clearly defined the civil aviation industry as an important strategic industry in the national economic and social development, and the competition among airlines is becoming more and more fierce. So the good corporation image and social benefits are becoming more and more important. To sum up, the k value should be in conservative and neutral type ($k<1$ or $k=1$). As shown in Table 9, GE CF6-80E1 is the best scheme.

4 Conclusions

Engine selection is essential to the airline in purchasing aircraft. It can directly affect the airline's future operation and social benefits. However, at present, the research on the engine are qualitative or one-sided. The airlines still lack a quantitative comprehensive and feasible method in the actual purchasing process.

In this paper, we use the utility theory to construct the evaluation model, and use the real data to improve the validity of the model selection results. On the basis of the previous results, a relatively comprehensive civil aviation engine evaluation index system is established, considering the engine reliability, economic efficiency, competitiveness, environmental protection level and the capacity for sustainable development.

In addition, we also combined the qualitative and quantitative methods. The subjective attitudes of different subjects are displayed in the final selection, that is the selection of k-the people's attitudes are quantified and integrated into the structure of the utility function. Combined with the AHP method for quantitative analysis of the weight of each index, the needs for different airlines to select engines is personalized when purchasing aircraft is realized.

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Prof. **Ding Songbin** is currently a professor in College of Civil Aviation at Nanjing University of Aeronautics and Astronautics. His research interests include aircraft performances and aeroplane safety system.

Ms. **Wang Xiaoli** is currently an M. E. candidate of Civil Aviation at Nanjing University of Aeronautics and Astronautics. Her research interest include safety of civil aviation.

Mr. **Wang Hongyu** is currently an M. E. candidate of College of Civil Aviation at Nanjing University of Aeronautics and Astronautics. His research interests include transportation planning and management of civil aviation.

(Executive Editor: Zhang Bei)