

A Decision-Making Method for Landing Routes of Aircraft on the Carrier

Yu Wu, Wenqian Tan, Liguo Sun and Xiangju Qu

School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China

Abstract. The landing safety of aircraft is of great significance for the normal operation of an aircraft carrier. This paper presents an optimal method for landing routes of aircraft. Owing to the fuzziness of environmental information and human judgment, a decision-making method is introduced to reduce the workload of landing console operators (LCO). Specifically, a route option method for aircraft landing is proposed based on Fuzzy Multi-attribute Group Decision Making (FMAGDM). Firstly, the route option problem is described. Then the essential elements of route option are described. A group decision-making method is proposed, and the most reasonable landing route in current environment is obtained considering the knowledge composition and the weight of each decision maker. Finally, simulations under different environments are conducted. The results indicate that the decision-making method is able to adapt to the environment changes, and determine the most reasonable route for each validation case.

1 Introduction

Landing aircraft on an aircraft carrier is a task laden with inherent risks [1]. There exist numerous uncertainties during the flight before the aircraft landing, e.g. the flight condition and the maritime environment [2], [3]. As a result, it increases the uncertainty of landing. The landing console operator (LCO) is in charge of determination of landing route [4], [5]. He/she makes decisions for the guidance of aircraft within a short time according to his knowledge and the information displayed on the instruments [6]. However, reasonable judgment is usually not able to be made quickly and accurately due to the fuzziness of the information. Artificial intelligence (AI) is suitable for dealing with fuzziness problem and is introduced to the route decision-making system of aircraft in order to reduce the workload of LCO.

Unlike the path planning problem [7], [8], the route modes for landing of carrier aircraft are fixed. The landing route is chosen for aircraft before they reach the aircraft carrier. It is the first step in the landing guidance support system. This issue is obviously essential to the automatic landing system and thus worthwhile to study in depth.

The aircraft usually adopt different routes to land depending on its performance, the traffic conditions, a variety of weather conditions and visibility [9]. Some biases or even errors may occur if we only rely on the judgments of human. Therefore, a decision-making system for route option is essential to reduce the workload of staffs and improve the safety level of landing.

The main contribution of this paper is to point out the necessity and importance of researching the route option problem for aircraft landing, and have a comprehensive

description of the problem. The establishment of mathematical model and the proposed method provide a valuable reference for assistant decision of the pilot and LCO. This group decision-making method is crucial to realize the intelligent decision-making.

2 Problem description and essential elements analysis

2.1 Problem description

The air control system sends return command to an aircraft in flight. Specifically, Tactical Air Navigation (TACAN) provides the position and distance information. The airborne early warning (AEW) provides the overall air traffic situation. The sea weather is measured by the observatory set up on the aircraft carrier, and the weather measurements are transmitted to a pilot. The route option problem is further depicted in Fig. 1.

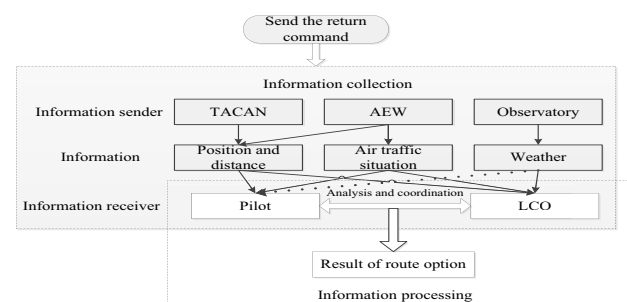


Figure 1. Problem description of route option

The dotted arrow denotes the receiver will only view the information as a reference to make a judgment. The pilot and the LCO are both decision makers when solving the route option problem. However, the LCO is chosen as the major decision maker in order to better master the air traffic situation and enhance the safety level of landing.

2.2 Analysis of essential elements

There are several essential elements in a route option problem. They will be discussed in this section.

2.2.1 The alternative routes

There are four modes of landing route according to the differences in atmospheric environment, performance of an aircraft and the air traffic situation.

① l_1 : The weather, visibility, performance of an aircraft and air traffic situation are all good when landing is permitted. The pilot lands the aircraft by vision under such conditions.

② l_2 : The weather and visibility are at a medium level and the performance of the aircraft and air traffic are in good conditions. A landing mode with higher safety standard will be adopted when clouds become heavy. It becomes dangerous to land the aircraft by vision.

③ l_3 : The weather and visibility are bad, the performance of the aircraft and air traffic are in good conditions. It is also unsafe to land the aircraft by vision in such conditions.

④ l_4 : The performance of aircraft is poor or the air traffic is in a bad condition. No proper conditions exist for aircraft landing on the carrier. In this case, the pilot has to get in touch with the land base for emergency landing.

2.2.3 The contributing factors:

The contributing factors for a route option problem are concluded as follows:

① Weather

It is usually difficult to predict the weather around a large area accurately. Only the nearby weather condition can be mastered continuously.

② The height of clouds

The vision of a pilot will be affected when the clouds are low or cover a wide range of the sky. The heavy cloud may even lead to a bump of an aircraft during the flight.

③ Visibility

The level of visibility plays an important role in affecting the visual observation and the judgment of a pilot.

④ Performance of aircraft

The aircraft is usually in good performance during flight. However it may get damaged when accidents occur.

⑤ Air traffic situation

The aircraft under consideration refers to the status of other aircraft which are near to the landing routes.

3 FMAGDM (Fuzzy multi-attribute group decision making) based method of route option

The FMAGDM method has a good description of the current environmental information and the weights of decision-makers [10], [11]. According to the developed fuzzy TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) approach [12], the triangular membership function is used to describe the performance ratings of contributing factors (short for PRCF for convenience in the rest of this paper). The PRCF is the knowledge base of the model which can be evaluated in advance. Similarly, the current environmental vector which is the input of the route option model can be also described by the triangular membership function. Subsequently a mathematical model is established to measure each alternative route. Based on this, the fuzzy judgment method for group decision-making is introduced to get the most reasonable one for the current environment.

3.1. Description of the PRCF and the current environmental vector

The PRCF or the current environmental vector needs to be described using fuzzy linguistic variables. The triangular membership function is introduced to define the value of each fuzzy linguistic variable. The properties of the triangular membership function are presented.

Definition 1: The mean value of a triangular membership function $a=[a^L, a^M, a^U]$ is defined as

$$s(a) = (a^L + 2a^M + a^U) / 4 \quad (1)$$

The mean value can be used to sort the triangular membership functions. In view of the triangular membership functions a and b , there exists a definition as follows: $a \geq b$ if $s(a) \geq s(b)$ and $a < b$ if $s(a) < s(b)$.

Definition 3: Assume U is a universe of discourse and define the α -cut set a_α as

$$a_\alpha = \{x \in U \mid \mu_x(x) \geq \alpha\}, \alpha \in [0, 1] \quad (2)$$

where a_α can be expressed as $a_\alpha = [a^L(\alpha), a^R(\alpha)]$, as shown in Fig. 2.

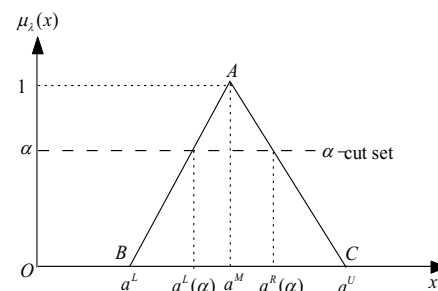


Figure 2. Definition of α -cut set

Definition 4: Assume a and b are two triangular membership functions and $a \geq b$, the fuzzy distance between a and b is defined as follows.

$$d(a,b) = [\max\{\int_0^1 d^L(\alpha)d\alpha, 0\}, d^L(1), \int_0^1 d^R(\alpha)d\alpha] \quad (3)$$

where $d^L(\alpha)$ and $d^R(\alpha)$ are defined as below:

$$\begin{cases} d^L(\alpha) = a^L(\alpha) - b^R(\alpha) \\ d^R(\alpha) = a^R(\alpha) - b^L(\alpha) \end{cases} \quad (4)$$

3.2 Decision-making with the developed fuzzy TOPSIS approach

5 contributing factors determine the result of route option. They (weather, clouds height, visibility, performance of aircraft and air traffic situation) are written as f_1, f_2, f_3, f_4 and f_5 respectively. The performance ratings of contributing factors are shown in Table 1.

Table 1. Description of performance ratings

	f_1	f_2	f_3	f_4	f_5
l_1	Good	>3000 feet	>5 km	Medium	Good
l_2	Bad	1000- 3000 feet	>5 km	Good	Good
l_3	Terrible	< 1000 feet	< 5km	Good	Good
l_4	Indifferent	Indifferent	Indifferent	Bad	Bad

The descriptions mentioned above need to be unified with the same linguistic variables as shown in Table 2.

Table 2. Unified linguistic variables of performance ratings.

Linguistic variable	No	Low	Medium	High	Very high
Expression	NO	LO	ME	HI	VH

All linguistic variables in Table 2 will be described by triangular membership functions in later usage. Suppose that the performance rating of $l_j(j=1,2,3,4)$ with respect to $f_i(i=1,2,3,4,5)$ is written as $e_{ij}=[e_{ij}^L, e_{ij}^M, e_{ij}^U]$ (the value of e_{ij} can be chosen from Table 2), then the fuzzy decision matrix for the route option problem can be established as follows:

$$D = \begin{bmatrix} e_{11} & e_{12} & e_{13} & e_{14} \\ e_{21} & e_{22} & e_{23} & e_{24} \\ \vdots & \vdots & \vdots & \vdots \\ e_{51} & e_{52} & \dots & e_{54} \end{bmatrix} \quad (5)$$

where matrix D is the knowledge base which has been mastered in advance. The matrix D can assist a pilot or LCO to make optimal decision.

The detailed procedure of the method will be provided.

Step 1: Normalize of the fuzzy decision matrix

Different contributing factors use different measurement units when collecting raw data. Therefore, normalization is needed to transform e_{ij} into the interval of $[0,1]$ in order to eliminate anomalies. In this paper, a linear transformation is adopted to get the normalized fuzzy decision matrix X :

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ \vdots & \vdots & \vdots & \vdots \\ x_{51} & x_{52} & \dots & x_{54} \end{bmatrix} \quad (6)$$

Since the PRCF denote efficiency in route option, x_{ij} can be normalized using the largest value, i.e., efficiency, of this contributing factor:

$$x_{ij} = [e_{ij}^L / e_i^{U \max}, e_{ij}^M / e_i^{U \max}, e_{ij}^U / e_i^{U \max}] \quad (7)$$

with $e_i^{U \max} = \max_{1 \leq j \leq 4} \{e_{ij}^U\}$ ($i=1,2,\dots,5 ; j=1,2,3,4$). Using Eq. (7), all linguistic variables are transformed into the interval of $[0,1]$.

We write the pilot and the LCO as decision maker 1 and 2. The normalized fuzzy decision matrix X_1 and X_2 can be established according to the knowledge and experience of decision makers.

$$X_1 = \begin{bmatrix} HI & ME & LO & NO \\ VH & HI & LO & NO \\ VH & VH & LO & LO \\ ME & HI & HI & LO \\ ME & HI & HI & LO \end{bmatrix} \quad X_2 = \begin{bmatrix} HI & ME & NO & NO \\ HI & ME & LO & NO \\ HI & HI & LO & NO \\ ME & HI & HI & ME \\ HI & VH & VH & LO \end{bmatrix}$$

Step 2: Integrate the current environment vector reported by a decision maker into the normalized fuzzy decision matrix

The environmental vector can also be described using linguistic variable, as shown in Table 3.

Table 3. Linguistic variable of environmental vector.

Linguistic variable	Too poor	A little poor	Normal	Good	Very good
Expression	TP	LP	NO	GO	VG

We denote the environmental evaluation of each contributing factor as $\omega_i=[\omega_i^L, \omega_i^M, \omega_i^U]$, which compose the environmental vector ($i=1,2,\dots,5$, the value of ω_i can be chosen from Table 3). The normalized fuzzy decision matrix integrating the environmental vector is calculated:

$$Z = (z_{ij})_{5 \times 4} = (\omega_i x_{ij})_{5 \times 4} = \begin{bmatrix} z_{11} & z_{12} & z_{13} & z_{14} \\ z_{21} & z_{22} & z_{23} & z_{24} \\ \vdots & \vdots & \vdots & \vdots \\ z_{51} & z_{52} & \dots & z_{54} \end{bmatrix} \quad (8)$$

Step 3: Determine the positive and negative ideal solutions

The positive ideal solution is obtained when each PRCF chooses its highest value from the fuzzy decision matrix D . On the contrary, the negative solution is obtained by choosing the lowest value for each performance rating.

The fuzzy positive ideal reference point (FPIRP) and negative point (FNIRP) are written as P and N in the remainder of this paper for convenience. The FPIRP and FNIRP can be defined as $P = (p_1, p_2, \dots, p_5)$ and $N = (n_1, n_2, \dots, n_5)$ with $p_i = \max_{1 \leq j \leq 4} \{z_{ij}\}$ and $n_i = \min_{1 \leq j \leq 4} \{z_{ij}\}$.

Step 4: Calculate the fuzzy distance between $l_j(j=1,2,3,4)$ and P (or N)

According to Eq. (3), the fuzzy distance between $l_j(j=1,2,3,4)$ and P (or N) are defined as follows:

$$d(l_j, P) = \sum_{i=1}^5 d(z_{ij}, p_i); d(l_j, N) = \sum_{i=1}^5 d(z_{ij}, n_i) \quad (9)$$

Step 5: Obtain the closeness coefficient

The larger the closeness coefficient is, the closer the alternative route is to the fuzzy ideal solution. Eq. (10) is adopted to calculate the closeness coefficient and distinguish the importance between FPIRP and FNIRP.

$$C(l_j) = \mu \frac{d(l_j, P)}{d(l_j, P) + d(l_j, N)} + (1 - \mu) \frac{d(l_j, N)}{d(l_j, P) + d(l_j, N)} \quad (10)$$

where $\mu(0 < \mu < 1)$ is a weight for different distances from FPIRP and FNIRP, it is determined by the subjective attitude of a decision maker.

3.3 Group decision-making process

The main idea of solving the group decision problem is to regard the pilot and the LCO as two contributing factors, and view the group decision-making problem as a single person decision-making problem. The group fuzzy decision matrix is constructed as follows:

$$O = \begin{bmatrix} o_{11} & o_{12} & \dots & o_{14} \\ o_{21} & o_{22} & \dots & o_{24} \end{bmatrix} \quad (11)$$

where O_{st} ($s=1,2$; $t=1,2,3,4$) is the closeness coefficient $C(l_j)$, which is calculated using Eq. (10). The group solution is depicted by the following steps:

Step 1: The weights of pilot and LCO are assumed as $\lambda_1 = [\lambda_1^L, \lambda_1^M, \lambda_1^U]$ and $\lambda_2 = [\lambda_2^L, \lambda_2^M, \lambda_2^U]$ respectively. The weighted normalized group fuzzy decision matrix is written as $V = (v_{kj})_{2 \times 4}$ ($k=1,2$; $j=1,2,3,4$).

Step 2: Write the fuzzy positive group ideal reference point (FPGIRP) and negative point (FNGIRP) as GP and GN respectively. The FPGIRP and FNGIRP can be formulated as $GP = (gp_1, gp_2)$ and $GN = (gn_1, gn_2)$ where

$$gp_k = \max_{1 \leq j \leq 4} \{v_{kj}\} \text{ and } gn_k = \min_{1 \leq j \leq 4} \{v_{kj}\}.$$

Step 3: Calculate the fuzzy distance between $l_j(j=1,2,\dots,4)$ and the FPGIRP (or FNGIRP), and calculate the closeness coefficient.

$$d(l_j, GP) = \sum_{k=1}^2 d(v_{kj}, gp_k); d(l_j, GN) = \sum_{k=1}^2 d(v_{kj}, gn_k) \quad (12)$$

$$GC(l_j) = \eta \frac{d(l_j, GP)}{d(l_j, GP) + d(l_j, GN)} + (1 - \eta) \frac{d(l_j, GN)}{d(l_j, GP) + d(l_j, GN)} \quad (13)$$

where $\eta(0 < \eta < 1)$ denotes the attitude of the group. It reflects the different importance of FPGIRP and FNGIRP.

Step 4: Calculate the mean values ($GC(l_j)$) according to Eq. (1). The route corresponding to $\max_{1 \leq j \leq 4} \{s(GC(l_j))\}$ is the most reasonable one in the current environment.

4 Results and analyses of route option in different environments

Real cases are presented to illustrate the validity of the proposed method. Two different environmental conditions are used as test scenarios. On the basis of a-priori knowledge, experience, current environment evaluations and weights of decision makers, the decision-making method is expected to choose the most reasonable route for the current environment. Further analysis of the simulation results implies that the proposed method has a bright future for real application in a practical project.

4.1 initialization and their fuzzy descriptions

The expressions of performance ratings and environment evaluations are shown in Table 4.

Table 4. Performance ratings and environment evaluations

	Performance ratings	Environment evaluations	Membership function
	NO	TP	[0,0,0.1]
Linguistic variables	LO	LP	[0.1,0.3,0.5]
and	ME	NO	[0.3,0.5,0.7]
expressions	HI	GO	[0.5,0.7,0.9]
	VH	VG	[0.9,1,1]

In order to compare the results in different environments, 2 pairs of simulations are carried out independently. The environment settings and evaluations of decision makers are listed in Table 5 and Table 6.

Table 5. Environment set to simulate

Serial number of simulation	Environments
i	The weather, clouds height and visibility are good while the performance of aircraft and air traffic situation are normal.
ii	The weather, clouds height and visibility are bad while the performance of aircraft and air traffic situation are good.

Table 6. Environment evaluations of decision makers

Contributing factors	Simulation i		Simulation ii		Weight
	Pilot	LCO	Pilot	LCO	
f_1	VG	GO	TP	TP	Pilot : $\lambda_1 =$ [0.4,0.5,0.6]
f_2	VG	GO	TP	TP	
f_3	VG	GO	TP	TP	LCO : $\lambda_2 =$ [0.8,0.9,1]
f_4	NO	GO	GO	GO	
f_5	NO	GO	GO	VG	

4.2 Results and analyses

The proposed decision-making method is applied to determine the optimal route for different environment conditions. The results are given in Table 7 and Table 8.

Table 7. Results of simulation i

Alternative route	Closeness coefficient	Mean value	Route option result
l_1	[0,0.82,161.06]	40.67	l_1
l_2	[0,0.80,159.28]	40.22	
l_3	[0,0.51,107.62]	27.16	
l_4	[0,0.20,55.49]	13.97	

Table 8. Results of simulation ii

Alternative route	Closeness coefficient	Mean value	Route option result
l_1	[0,0.51,5.24]	1.57	l_3
l_2	[0,0.80,5.89]	1.87	
l_3	[0,0.80,6.41]	2.00	
l_4	[0,0.20,2.84]	0.81	

From Simulation i to Simulation ii, the environment condition set for each validation case is degrading gradually. With the changes of the environment setups, the decision-making method is able to adapt to the environment changes, and determine the most reasonable route for each validation case. The results indicate that the proposed method has the capability of dealing with the fuzziness in description successfully and can solve the troubles introduced by artificial decision-making. Above all, the proposed decision making approach is able to assist the pilot and the LCO to guide the aircraft to land safely and automatically. The proposed method can be used for air traffic control in an aircraft carrier. It can assist the LCO to make the landing route scheduling decision, and can provide the security information for the returning aircraft after having finished a combat or patrol mission.

5 Conclusion

In this paper, the route option problem of aircraft landing on an aircraft carrier is solved by proposing a new decision-making method. Firstly, the route option problem and the essential elements are described. Then using the improved fuzzy TOPSIS approach, fuzziness in description and judgment can be solved by introducing linguistic variables. Subsequently, a mathematical model, which can be later applied to measure the rationality of each alternative route for the current environment, is established. Finally, the group decision-making approach is introduced to take into account the judgments of both the LCO and the human pilot. Validation results for

different environment setups indicate that the proposed decision-making method can adapt to the changes of environment and can make a quick and realistic decision.

The decision-making method proposed in this paper can reduce the workload of the pilot and the LCO by pointing out the optimal route option for the returning aircraft. The work of this paper provides a solution for landing route scheduling, which should be addressed at the first order to realize the automatic landing of carrier aircraft. Automatic flight controller design should be viewed as the future work under the framework of realizing automatic landing of aircraft.

Acknowledgement

This research work is financially supported by the National Natural Science Foundation of China (NSFC) with the project reference number of 11502008.

References

1. S. Newman, Shipborne aviation: an introduction. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 219.5 (2005): 363-368.
2. M.B. Subrahmanyam, H-infinity design of F/A-18A automatic Carrier Landing System. *Journal of guidance, control, and dynamics* 17.1 (1994): 187-191.
3. M.G. Petovello, et al. Measuring aircraft carrier flexure in support of autonomous aircraft landings. *Aerospace and Electronic Systems, IEEE Transactions on* 45.2 (2009): 523-535.
4. K. L. Gold, and Alison K. Brown. A hybrid integrity solution for precision landing and guidance. *Position Location and Navigation Symposium, 2004. PLANS 2004*. IEEE, 2004.
5. N. Polmar, *The Naval Institute guide to the ships and aircraft of the US fleet*. Naval Institute Press, 2005.
6. K. M. Adams and T. J. Meyers. The US Navy carrier strike group as a system of systems. *International Journal of System of Systems Engineering* 2.2-3 (2011): 91-97.
7. A. Shinkafi and C. Lawson, Development of a tool to study aircraft trajectory optimisation in the presence of icing conditions. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 229.8 (2015): 1464-1484.
8. Y. Wu and X.-J. Qu. Obstacle avoidance and path planning for carrier aircraft launching. *Chinese Journal of Aeronautics* 28.3 (2015): 695-703.
9. A. G. Shem, Thomas Mazzuchi, and Shahram Sarkani. Addressing uncertainty in UAV navigation decision-making. *Aerospace and Electronic Systems, IEEE Transactions on* 44.1 (2008): 295-313.
10. P. Liu, A weighted aggregation operators multi-attribute group decision-making method based on interval-valued trapezoidal fuzzy numbers. *Expert Systems with Applications* 38.1 (2011): 1053-1060.
11. B. Vahdani, et al. A new compromise solution method for fuzzy group decision-making problems with an application to the contractor

- selection. *Engineering Applications of Artificial Intelligence* **26.2** (2013): 779-788.
12. R. K. Singh and L. Benyoucef. A fuzzy TOPSIS based approach for e-sourcing. *Engineering Applications of Artificial Intelligence*, **24** 3 (2011): 437-448.