Anti-UAV Group Effectiveness Evaluation Based on Fuzzy Analytic Hierarchy Process

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Abstract. Firstly, according to the mode of UAV fleet operation and air defense means, the model of operational effectiveness evaluation system for anti-UAV fleet is built. Then, a fuzzy analytic hierarchy process based on triangular fuzzy number to represent importance is selected to determine the weights of different indexes in the system. The validity of the model is verified by evaluating two examples, the US Nimitz and the Russian Kuznetsov. The laser weapon, high power microwave weapon and electronic jamming equipment in the Nimitz carrier have been improved for the anti-UAV fleet operation effect, which has been evaluated to be better than before.

Keywords: Triangular fuzzy number, fuzzy tomography, operational efficiency, effectiveness evaluation.

1. Introduction

In recent years, with the rapid development of micro-system technology, communication and navigation technology and artificial intelligence technology, the smart way of UAV battle will likely overturn the rules of future wars. UAV fleet operation refers to the bee swarm operation system composed of a large number of small UAVs with low cost, which relies on technologies such as large data, artificial intelligence, wireless self-organizing network and so on. In the future battlefield, the supersaturated attack on operational targets by a large number of unmanned aerial vehicles can effectively improve the operational efficiency of our side [1].

The relationship between spear and shield is always mutually complementary. The development of UAV fleet operations also promotes the development of anti-UAV fleet operations. In the current anti-UAV fleet operations, there are hard killing means such as fire destruction and soft killing means such as electronic warfare interference. Both methods have their own advantages and disadvantages. The future trend is to use all kinds of soft and hard killing methods in a comprehensive way. There are many soft and hard killer weapons on the warship, so the optimal configuration of combat equipment is needed in the face of unmanned air fleet. This paper mainly studies an anti-UAV group operational effectiveness evaluation system based on warships, and establishes a set of warship anti-UAV group operational effectiveness evaluation system through fuzzy layer analysis method, which provides guidance for warship anti-UAV group operations [2].

Fuzzy Analytic Hierarchy Process (AHP) is a quantitative and qualitative system analysis method. In the evaluation process, complex problems are divided into many indicators, which are grouped
according to the membership relationship to form an orderly hierarchy. In each layer, the relative importance of each element against the goals of the previous layer is derived by comparing them. Finally, the weight values of each index relative to the target elements are synthesized by mathematical methods.

The steps of fuzzy analytic hierarchy process are as follows: (1) decompose the target into many criteria and indicators with causality, and establish a comprehensive evaluation system; (2) compare each index under the same criterion, determine the relative importance according to the evaluation standard, and establish the fuzzy judgment matrix; (3) determine the weight of each target element through mathematical calculation; (4) establish a comprehensive evaluation system through comprehensive evaluation The optimal comprehensive evaluation result is obtained by ranking all the alternatives [3].

2. Combat effectiveness evaluation system of warship anti UAV group

In order to combat UAV group, the first step is to carry out detection and reconnaissance, and then take effective means of deception protection or interception and damage. The current anti UAV strategy is mainly composed of detection, tracking and early warning, camouflage protection, deception jamming and strike damage. In this paper, combined with the actual situation of the ship, according to the above four kinds of criteria, the combat effectiveness evaluation system of ship anti UAV group is established, as shown in Figure 1.

![Figure 1. Combat effectiveness evaluation of anti UAV group.](image)

2.1. Detection, tracking and warning

Because of its small size and low endurance, unmanned aerial vehicle (UAV) must be transported by carrier to the ship in a short distance before it can operate independently. Medium and long range warning radar is used to detect and track the carrier when the distance is far. The specific indicators are: equipment number D1, maximum detection range D2, target tracking number D3 [4]. UAV group usually adopts low altitude flight strategy to avoid radar detection, and low altitude blind compensation radar in the system detects UAV group in low altitude flight. The specific indicators are: the number of equipment D4, the maximum detection distance D5, the maximum detection height D6, detection accuracy D7. Radio reconnaissance can detect the navigation, guidance, remote control and other radio signals of UAV group, and judge the deployment and trend of UAV Group [5].

The specific indicators are: equipment quantity D8, detection accuracy D9, frequency measurement range D10. The specific indicators are: equipment quantity D11, detection accuracy D12, maximum detection distance D13. The AWACS search and monitor air and sea targets, use electronic equipment to detect hostile targets, and transmit information to the ship command center. The specific indicators are: the number of equipment D14, the maximum detection range D15, the number of target tracking D16.
2.2. Camouflage Protection
UAV group will select some high-value targets on the warship to achieve the combat purpose through super saturation attack. Ships can camouflage radar and other high-value targets, and use infrared, microwave, radio and other technologies to deceive and induce UAVs [6]. Camouflage protection system is divided into camouflage deception and decoy misleading. The specific indicators are: camouflage area D17, type number D18, camouflage equipment quantity D19, guidance equipment quantity D20, induction time length D21.

2.3. Deceptive interference
Radio interference affects the contact between UAV and command center and between UAVs. The specific indicators are: equipment quantity D22, jamming quantity D23, jamming frequency band D24 and jamming power D25. Navigation interference affects the flight path of UAV and makes it lose the guidance of satellite navigation. The specific indicators are: equipment quantity D26, jamming distance D27, jamming power D28. The strong acoustic interference affects the inertial navigation module of UAV, which makes it lose its direction and autonomous coordination ability after losing satellite navigation. The specific indicators are: equipment quantity D29, jamming distance D30. By blocking the data link of the UAV, the link capture invades the command system to control the UAV [7]. The specific indicators are: equipment quantity D31, capture sorties D32.

2.4. Blow damage
Dense array is the last line of defense for UAV group. The specific indexes are: equipment quantity D33, hit rate D34, firing rate D35 and ammunition storage D36. The intercepting missile can destroy the carrier of intercepting UAV and play the greatest combat effectiveness. The specific indicators are: equipment quantity D37, hit rate D38, stored ammunition D39. Laser weapon is an ideal weapon to deal with individual UAV because of its fast reaction speed and fast firepower transfer. The specific indexes are: the number of equipment D40, the hit rate D41, the single light time D42. High power microwave weapon is the electronic equipment that destroys UAV by using high power microwave beam, which makes UAV lose performance. The specific indexes are: equipment quantity D43, transmitting power D44, hit rate D45. Carrier based aircraft can attack UAVs in the air to protect the safety of ships [8]. The specific indicators are: equipment quantity D46, maximum speed D47, maximum range D48.

3. Weight determination of evaluation system
3.1. Triangular Fuzzy Numbers
Definition 1: Set the fuzzy set on domain $\mathbb{R}$ to $M$, and the membership function $\mu_M : \mathbb{R} \rightarrow [0,1]$ of $M$ to

$$\mu_M(x) = \begin{cases} \frac{x-l}{m-l} & x \in [l,m] \\ \frac{x-u}{m-u} & x \in [m,u] \\ 0 & \text{otherwise} \end{cases}$$

(1)

Where $l \leq m \leq u$, $l$ and $u$ are the lower and upper bounds of $M$ [9]. $l$ and $u$ are fuzzy degrees. The larger $u-l$ is, the stronger the degree of fuzziness is. $m$ is the value when the membership degree of fuzzy set $M$ is 1. Geometric interpretation of triangular fuzzy numbers [10]:
The triangular fuzzy number $M$ is expressed as $(l, m, u)$, where $x = m$, $x$ completely belongs to $M$, $l$ and $u$ are the lower and upper bounds respectively. Except $l$, $u$, the fuzzy number $M$ does not belong to.

Definition 2 [10]: if there are two triangular fuzzy numbers $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the basic operation of triangular fuzzy numbers is as follows:

$$M_1 \oplus M_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$$  \hfill (2)

$$M_1 \odot M_2 = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2)$$  \hfill (3)

$$\lambda \odot M_1 = (\lambda \times l_1, \lambda \times m_1, \lambda \times u_1)$$  \hfill (4)

$$1/M_1 = (1/l_1, 1/m_1, 1/u_1)$$  \hfill (5)

3.2. Constructing a Judgement Matrix

A judgment matrix is a matrix formed by comparing the same level of features in a hierarchy with the previous level of goals in terms of importance. In fuzzy analytic hierarchy process, we construct a triangular fuzzy number based judgment matrix $B = (b_{ij})_{n \times n}$, $b_{ij} = [l_{ij}, m_{ij}, u_{ij}]$, where $m_{ij}$ is the median, $l_{ij}$ and $u_{ij}$ are the lower and upper bounds respectively. In the process of evaluation, there are usually many people to judge. We take the mean of each element as the final judgment matrix, which is derived from the following formula

$$h_i = \frac{1}{N} \sum_{j=1}^{N} (j_{ij} + \cdots + j_{ij})$$  \hfill (6)

Table 1. Scales and their meanings [11].

| Scale | Meaning |
|-------|---------|
| $M_1$ | Two elements are equally important |
| $M_2$ | The front is slightly more important than the back |
| $M_3$ | The front is obviously more important than the back |
| $M_4$ | The front is mightily more important than the back |
| $M_5$ | The front is absolutely more important than the back |
| $M_6$, $M_7$, $M_8$, $M_9$ | Median of two scales |
Based on triangular fuzzy number and scaling method, a triangular fuzzy number judgment matrix of warship anti-UAV fleet operational effectiveness evaluation system is established. The final comprehensive triangular fuzzy number judgment matrix is obtained by formula (6), which is scored by more than one person.

3.3. Weight Determination Algorithm
In the triangular fuzzy number judgment matrix, the size between the upper boundary $u$ and the lower boundary $l$ of the judgment interval indicates the degree of ambiguity of the judgment. The larger the $u-l$, the more ambiguous the judgment, and the smaller the $u-l$, the clearer the judgment. When $u-l=0$, the judgment is clear. There are many weight algorithms in Fuzzy Analytic Hierarchy Process. By contrast, it is decided to use the algorithms in the literature [12] to calculate the weights.

(1) Construct the fuzzy evaluation factor matrix as follows:

$$H = \begin{pmatrix}
1 & \cdots & 1 - \frac{u_m - l_m}{2m_n} \\
\vdots & \ddots & \vdots \\
1 - \frac{u_m - l_m}{2m_n} & \cdots & 1
\end{pmatrix}$$

(7)

In the formula, $\frac{u_m - l_m}{2m_n}$ denotes the degree of ambiguity. The greater the value, the greater the degree of ambiguity. Conversely, the less ambiguous the degree.

(2) Adjust the judgment matrix by $Q = M \times H$, in which the $M$ matrix is composed of the original judgment matrix $m_{ij}$.

(3) Converts the new Judgment Matrix $Q$ into Judgment Matrix $P=(p_{ij})_{n \times n}$ with a diagonal of 1 by column and satisfies $p_{ij} = 1/p_{ji}$.

(4) Compatibility matrix analysis of matrix $P$ yields a compatibility matrix $R=(r_{ij})_{n \times n}$, where $R$ satisfies the consistency condition $r_{ij} = r_{ik} \cdot r_{kj} (k = 1, 2, \cdots, n)$ and $r_{ij} = 1/r_{ji}$. The value of $r_{ij}$ is calculated in formula $r_{ij} = \prod_{k=1}^{n} p_{ik} \cdot p_{kj}$.

(5) Calculate the weight $\omega_i$ of each index at this level and calculate it by formula [13]

$$\omega_i = c_i \sum_{k=1}^{n} C_k \ (i=1,2,\cdots,n)$$

(8)

$$c_i = \frac{1}{\prod_{k=1}^{n} r_{ik}} \ (i=1,2,\cdots,n)$$

(9)

3.4. Weight Results
Write a program to calculate the weights of each level.

(1) The weight of each index of Goal A is:

$$\omega_A = (0.2550, 0.2016, 0.2604, 0.2829)$$

(2) The weights of criterion layer B are

$$\omega_{b1} = (0.1871, 0.2271, 0.1935, 0.1781, 0.2142) \quad \omega_{b2} = (0.3356, 0.6644) \quad \omega_{b3} = (0.2827, 0.2942, 0.1676, 0.2556)$$

$$\omega_{b4} = (0.2191, 0.1758, 0.2012, 0.2184, 0.1854)$$

(3) The weights of the constraint layer C are:

$$\omega_{c1} = (0.3907, 0.2343, 0.3751) \quad \omega_{c2} = (0.2581, 0.2315, 0.2572, 0.2532) \quad \omega_{c3} = (0.3056, 0.2810, 0.4134)$$

$$\omega_{c4} = (0.3433, 0.2901, 0.3666) \quad \omega_{c5} = (0.3932, 0.2332, 0.3736) \quad \omega_{c6} = (0.3445, 0.2278, 0.4277) \quad \omega_{c7} = (0.5409, 0.4591)$$

$$\omega_{c8} = (0.2390, 0.2185, 0.2772, 0.2653) \quad \omega_{c9} = (0.3597, 0.3067, 0.3336) \quad \omega_{c10} = (0.5012, 0.4988) \quad \omega_{c11} = (0.5012, 0.4988)$$

5
\[ \omega_C = (0.2462, 0.2256, 0.2313, 0.2968) \]
\[ \omega_C = (0.3415, 0.2508, 0.4077) \]
\[ \omega_C = (0.3666, 0.3259, 0.3074) \]
\[ \omega_C = (0.3378, 0.2723, 0.3899) \]
\[ \omega_C = (0.4385, 0.2859, 0.2756) \]

(4) The final weight of each index D is:
\[ \omega = (0.0186, 0.0112, 0.0179, 0.0149, 0.0134, 0.0149, \ldots) \]
\[ D_1 = 407 \]
\[ D_2 = 370 \]
\[ D_3 = 407 \]

4. Example Analysis
In military, UAV fleet is an attack weapon, especially in naval warfare. A large enough UAV fleet can pose a serious threat to ships, and the operational capability of ships will be reduced after they are attacked by UAV fleet. Therefore, it is of great significance to study the operational effectiveness of warship anti-UAV fleet.

This paper chooses Nimitz class carrier, Kuznetsov carrier and the improved version of Nimitz carrier with the addition of laser weapons, microwave weapons and other anti-UAV equipment to study. Example one is Nimitz carrier equipment, example two is Kuznetsov carrier equipment, and example three is improved Nimitz carrier equipment. The validity of the evaluation model is verified by comparing the example one and the example two, and the effectiveness of increasing the operational effectiveness of anti-UAV equipment is verified by comparing the example one and the example three. Through the comparison of different examples, the effect of various weapons equipped is analyzed to provide reference for future aircraft carrier construction of our army.

| B1 | C1 | C2 | C3 | C4 | C5 |
|----|----|----|----|----|----|
| D  | D1  | D2  | D3  | D4  | D5  | D6  | D7  | D8  | D9  | D10 | D11 | D12 | D13 | D14 | D15 | D16 |
| 1  | 3   | 407 | 100 | 0   | 0   | 0   | 0   | 2   | =0.5 | 0.55-20 | 0   | 0   | 0   | 5   | 741 | 250 |
| 2  | 3   | 407 | 100 | 0   | 0   | 0   | 0   | 2   | =0.5 | 0.55-20 | 0   | 0   | 0   | 2   | 250 | 200 |
| 3  | 407 | 100 | 1   | 210 | 12  | 50  | 2   | =0.5 | 0.55-20 | 0   | 0   | 0   | 5   | 741 | 250 |

| B2 | B3 | C6 | C7 | C8 | C9 | C10 | C11 |
|----|----|----|----|----|----|----|----|
| D  | D18 | D19 | D20 | D21 | D22 | D23 | D24 |
| 1  | 0   | 7   | 9   | 10  | 40  | 2   | 80  | 2   |
| 2  | 0   | 6   | 17  | 10  | 60  | 2   | 10  | 1   | 1.5 |
| 3  | 0   | 7   | 9   | 10  | 40  | 2   | 80  | 2   | 1   | 1.5 |

| B4 | C12 | C13 | C14 | C15 | C16 |
|----|-----|-----|-----|-----|-----|
| D  | D33 | D34 | D35 | D36 | D37 |
| 1  | 3   | 45  | 3000 | 989 | 5   |
| 2  | 4   | 50  | 3000 | 1550 | 8   |
| 3  | 3   | 45  | 3000 | 989 | 5   |

| B5 | C17 | C18 | C19 | C20 | C21 |
|----|-----|-----|-----|-----|-----|
| D  | D38 | D39 | D40 | D41 | D42 |
| 1  | 3   | 45  | 122 | 0   | 0   |
| 2  | 4   | 50  | 192 | 0   | 0   |
| 3  | 3   | 45  | 122 | 1   | 90  |

After collecting the data of instance one, two and three, sort it out according to the specific indicators in the ship anti-UAS combat effectiveness evaluation system, and then standardize the data processing [14]. The standardized processing values of each index are shown in Table 3.
Finally, the weights of each index in the ship anti-UAS group combat effectiveness evaluation system are multiplied with the standardized data in each instance to obtain the evaluation values of the anti-UAS group combat effectiveness in different examples, as shown in Table 4.

Table 3. Standardized processing values of various indicators.

| B | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| D | D1 | D2 | D3 | D4 | D5 | D6 | D7 | D8 | D9 | D10 | D11 | D12 | D13 | D14 | D15 | D16 |
| 1 | 0.6396 | 0.5948 | 0.3774 | 0 | 0 | 0 | 0 | 0.6667 | 0.5774 | 0.6112 | 0 | 0 | 0.6804 | 0.6878 | 0.6155 |
| 2 | 0.4264 | 0.5407 | 0.5774 | 0 | 0 | 0 | 0 | 0.3333 | 0.5774 | 0.5028 | 0 | 0 | 0.2722 | 0.2321 | 0.4924 |
| 3 | 0.6396 | 0.5948 | 0.3774 | 1 | 1 | 1 | 1 | 0.6667 | 0.5774 | 0.6112 | 0 | 0 | 0.6804 | 0.6878 | 0.6155 |

Table 4. Example evaluation values.

| Example one | Example two | Example three |
|-------------|-------------|---------------|
| 0.2576      | 0.2469      | 0.4294        |

The comparison of examples one and two shows that the combat effectiveness of the Nimitz aircraft carrier is higher than that of the Kuznetsov aircraft carrier, and there is not much difference. The comparison of Examples 1 and 3 shows that the combat effectiveness of aircraft carriers has been significantly improved after the addition of weapons and equipment for UAVs. In the construction of aircraft carriers, laser weapons, high-power microwave weapons, navigation jamming devices and other equipment specifically aimed at the UAV group can be added to respond to the growing threat of the UAV group.

5. Conclusion

Combining anti-UAS combat methods and ship air defense defense methods, this paper constructs a ship anti-UAS combat effectiveness evaluation system model from four aspects: detection, tracking and early warning, camouflage protection, deception jamming, and strike damage. The effectiveness of the model is verified through examples.

In recent years, UAV swarm technology has made great progress, and it is one step closer to actual combat applications. In the construction of our military’s equipment, we must increase weapons for the UAV group, including hard-kill weapons such as lasers and high-power microwaves, and soft-kill weapons such as electronic warfare jamming, to strengthen the ability of ships to counter UAV groups and respond to the ever-changing war environment.

References

[1] Chen Jing. Analysis of the low-cost UAV group technology of the US Navy [J]. Flying Missile, 2016, 373 (01): 24-26.
[2] Zhang Q, Chen J, Ji L, etal. Response Delay Optimization in Mobile Edge Computing Enabled UAV Swarm [J]. IEEE Transactions on Vehicular Technology, 2020, 69 (99): 3280-3295.
[3] Zhang Jijun. Fuzzy Analytic Hierarchy Process (FAHP) [J]. Fuzzy Systems and Mathematics, 2000, 14 (2): 80-88.
[4] Zhong Jilong, Guo Jilian. Combination analysis method of air long-range combat system effectiveness evaluation [J]. Systems Engineering, 2015, 263 (11): 140-145.
[5] Qu Feng, Yang Hua, Wang Lijun. Wireless sensor network and its application [J]. Ordnance
[6] Jiang Ning, Xu Xianyun. Threat environment and camouflage technology for air defense operations [J]. Aerospace Electronic Warfare, 2005, 021 (002): 61-62.

[7] Lei Zhongyuan, Liang Yizhi, Wang Zhe. Combat effectiveness evaluation of ship electronic warfare system based on fuzzy comprehensive evaluation [J]. Electronic Information Warfare Technology, 2006, 21 (004): 42-44.

[8] He Xiaojun, Xu Yang. Coordinated operations of ship-borne soft/hard kill weapon systems [J]. Mine warfare and ship protection, 2001, 000 (004): 41-44.

[9] Xu Zeshui. A sorting method of triangular fuzzy number complementary judgment matrix [J]. Journal of Systems Engineering, 2004, 19 (1): 47-50.

[10] Jiang Yanping, Fan Zhiping. A Practical Method for Ranking Triangular Fuzzy Number Complementary Judgment Matrix [J]. Systems Engineering, 2002, 20 (2): 89-92.

[11] Guo Jinyu, Zhang Zhongbin, Sun Qingyun. Research and application of analytic hierarchy process [J]. Chinese Safety Science Journal, 2008, 18 (005): 148-153.

[12] Luo Baofeng, Wang Qingxian, Zhu Junhu. A method for determining the weights of evaluation indicators based on triangular fuzzy numbers and analytic hierarchy process [J]. Telecommunications Technology Research, 2013, 382 (6): 9-16.

[13] Guo Liu, Gu Xuefeng, Liu Wangsuo. Evaluation of the technical status and effectiveness of the shipborne main gun weapon system during the voyage [J]. Ordnance Equipment Engineering Journal, 2018, 039 (005): 70-74.

[14] Wang Yuju, Yue Lijun. Satellite detection effectiveness evaluation algorithm based on fuzzy analytic hierarchy process [J]. Journal of System Simulation, 2012, 24 (008): 1665-1668.