Advances in Military Technology
Vol. 19, No. 1, 2024, pp. 177-188
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01885

Risks Assessment Concerning Non-Fulfillment of Asset Protection Tasks from Air Strikes

O. Zahorka, S. Polishchuk*, I. Zahorka and N. Fregan

National Defense University of Ukraine, Kyiv, Ukraine

The manuscript was received on 24 January 2024 and was accepted after revision for publication as research paper on 31 May 2024.

Abstract:

Taking into account the uncertainty of the enemy's air actions during the organization of assets protection from their strikes is a decisive factor in the successful task fulfillment by air defense forces. The impact of the enemy's air actions uncertainty is assessed by the task non-fulfillment risks by air defense forces to protect assets from enemy's strikes. The article describes the method of determining the task non-fulfillment risks by air defense forces based on the use of a fuzzy-multiple approach. The risk is advisable to be taken into account together with the results of evaluating the combat effectiveness of air defense forces when making decisions on the organization of assets protection from the enemy's air attack.

Keywords:

assets, air attack means, air defense, fuzzy-multiple approach, task non-fulfillment risk

1 Introduction

The organization of the assets protection by air defense forces (ADF) is carried out in conditions of uncertainty of the enemy's actions, which is caused mainly by the ambiguity of the direction of the strikes on the assets and the altitudes of the use of air attack means (AAM) [1-9]. When planning the air defense (AD) of assets, the effectiveness of the ADF usage is usually evaluated according to possible options of the enemy's actions, which are determined by a heuristic method, which is not quite sufficient for making informed decisions about the organization of assets protection [4-9]. In time of making decisions, it is also useful to consider the non-fulfillment risks of the task by ADF to protect assets from air strikes.

* *Corresponding author: Aviation and Air Defense Institute, National Defense University of Ukraine, Povitroflotskyi av. 28, UA-030 49 Kyiv, Ukraine. Phone: +380 672 789 704, E-mail: sergiy_pv@ukr.net. ORCID 0000-0001-9050-6918.*

2 Formulation of Problem and Setting Objective

Today, many methods of evaluating the effectiveness of AD of assets based on the use of simulation modeling methods, analytical, combined methods, and stochastic analysis have been developed and applied. The monographs [4, 5] provide an analytical-stochastic model for evaluating the combat effectiveness of ADF. The simulating of the combat operations of ADF is considered in the monographs [6, 7]. The application of the mass service theory methods for evaluating the effectiveness of the repulsion of cruise missiles by multi-channel AD systems is given in the monographs [8, 9].

From the analysis of the cited works, it can be stated that the existing methods allow a comprehensive assessment of the combat effectiveness of air defense forces and means. However, almost no attention is paid to determining the risks of non-fulfillment of tasks by ADF to protect assets from the strikes of air attack means (AAM).

The purpose of the article is to develop a methodology for determining the risks of non-fulfillment by ADF the task of assets protection from strikes of AAM in conditions of uncertainty of their use.

3 Methodology Description and Basic Mathematical Equations

The task of the air defense forces in assets protection is to destroy the required number of targets during the repulse of the AAM strike [1-9]. This is a decisive requirement for evaluation of the effectiveness of the ADF usage. Other tasks of ADF, in particular the permissible assets loss, the required probability of assets preservation, are determined taking into account the destruction of the required number of targets. An indicator of the combat effectiveness of ADF is the mathematical expectation of the relative number of targets δ_{des}, that are destroyed during the repulse of the AAM strike. The indicator δ_{des} is determined by the formula

$$\delta_{\text{des}} = \frac{M_{\text{des}}}{N} \tag{1}$$

where M_{des} – the mathematical expectation of the number of targets destroyed by ADF;
N – the number of AAM in the strike.

The mathematical expectation of the relative number of AAM that remain undamaged (δ_{ud}) is equal to

$$\delta_{\text{ud}} = \frac{N - M_{\text{des}}}{N} = 1 - \delta_{\text{des}} \tag{2}$$

Usually, risk is considered as an undesirable result of any activity. However, when organizing the assets protection from air strikes, it is advisable to consider the task non-fulfillment risk by ADF. Taking into account the determinability of the requirement to destroy the required number of targets, an indicator δ_{ud} was adopted to assess the task non-fulfillment risk by ADF.

The mathematical expectation of the number of targets that can be destroyed by the ADF depends significantly on the density of the AAM raid (λ). During the organization of the assets protection by ADF, only the range of possible changes in the density of the AAM raid is known, and the amount of the raid density itself can be considered uncertain.

For each density of AAM raids, using known methods of assessing the combat effectiveness of ADF, the mathematical expectation of the targets number that can be destroyed during the repulsion of the AAM raid can be determined.

The distribution laws of probabilities of the enemy's use of the strikes directions, the density of AAM in the strikes, and the use of altitudes by the AAM are unknown. This limits the application of probability theory methods when assessing the tasks non-fulfillment risks by ADF.

Taking into account the ambiguity of determining when organizing AD of assets, the direction of the strike of the AAM on the asset, the altitudes of their use, the density of the AAM in the strike, it is advisable to use a fuzzy-multiple approach [10-14]. The advantage of using the fuzzy-multiple approach is the possibility of taking into account uncertainty factors whose laws of probability distribution are unknown, subjective assessments, and linguistic uncertainty. For using the fuzzy-multiple approach, experts define terms that form functions of belonging to the degree of the enemy's use of the strikes' direction on assets $\varsigma(P_{\mathrm{str}})$ and the density of AAM in a strike from these directions $\nu(\lambda^*)$. In practice, triangular forms of affiliation functions have become widespread, which allow the easiest way to perform the operations on fuzzy sets [12, 14].

Five linguistic variables are used in fuzzy assessment by experts. They are very low (VL); low (L); average (AV); high (H); very high (VH). In the general case, triangular fuzzy numbers of terms correspond to: very low (VL) (0; 0; 0.25); low (L) (0; 0.25; 0.50); average (AV) (0.25; 0.50; 0.75); high (H) (0.50; 0.75; 1.00); very high (VH) (0.75; 1.00; 1.00).

For each direction of the AAM strike, when using a certain flight altitude, experts determine triangular numbers for the normalized relative to the maximum value of the density of AAM in the strike

$$\lambda^* = \frac{\lambda}{\lambda_{\max}} \quad \lambda > 0 \tag{3}$$

where $\lambda_{\max}$ – the maximum value of the density of AAM in the strike.

Given that $\lambda^* > 0$, to determine the triangular numbers of terms, the interval of linguistic variables is determined

$$\Delta = \frac{1 - \lambda^*_{\min}}{4} \tag{4}$$

where $\lambda^*_{\min}$ – the minimum value of the normalized density of AAM in the strike.

Because of this, in the case of a fuzzy estimation of the normalized density of AAM in the strike, the triangular fuzzy numbers of terms correspond to:

$$\left.\begin{array}{l} \mathrm{VL}\ \left(\lambda^*_{\min};\ \lambda^*_{\min};\lambda^*_{\min}+\Delta\right) \\ \mathrm{L}\ \left(\lambda^*_{\min};\ \lambda^*_{\min}+\Delta;\lambda^*_{\min}+2\Delta\right) \\ \mathrm{AV}\ \left(\lambda^*_{\min}+\Delta;\ \lambda^*_{\min}+2\Delta;\lambda^*_{\min}+3\Delta\right) \\ \mathrm{H}\ \left(\lambda^*_{\min}+2\Delta;\ \lambda^*_{\min}+3\Delta;\ 1\right) \\ \mathrm{VH}\ \left(\lambda^*_{\min}+3\Delta;\ 1;\ 1\right) \end{array}\right\} \tag{5}$$

Afterwards, in accordance with the linguistic variable determined by the experts, triangular fuzzy numbers (normalized densities) of terms are defined, which are used to evaluate the combat effectiveness of ADF using known methods [4 -9]. For the linguistic variable, the minimum ($M_{\text{des}}^{\min}$), average ($M_{\text{des}}^{\text{av}}$), maximum ($M_{\text{des}}^{\max}$) mathematical expectation of the targets number destroyed by ADF is determined. With the use of Eq. (2), triangular fuzzy mathematical expectations of the relative number of AAM that remain undamaged $\delta_{\text{ud}}^{\min}$, $\delta_{\text{ud}}^{\text{av}}$, $\delta_{\text{ud}}^{\max}$ are calculated to form the corresponding affiliation function.

In this way, the affiliation function of the normalized density of AAM in the strike $\nu(\lambda^*)$ is transformed into the affiliation function of targets not damaged by ADF during the reflection of the enemy's air strikes on assets $\mu(\delta_{\text{ud}})$.

Triangular fuzzy numbers of the affiliation function $\varsigma(P_{\text{str}})$ of the degree of the enemy's use of the strikes direction on the assets $P_{\text{str}}^{\min}$, $P_{\text{str}}^{\text{av}}$, $P_{\text{str}}^{\max}$, are determined in the usual way according to the linguistic variables provided by the experts.

When evaluating the combat effectiveness of ADF and the risk assessment of non-fulfillment of their tasks, it is necessary to consider the altitude of the AAM use. For this purpose, the possible altitudes of AAM use are divided into L ranges ($l = \overline{1, L}$). The use of air attack means of the l range of altitudes in the k direction of the strike ($k = \overline{1, K}$) is taken into account by the probability B_{lk}, set by the experts.

The risk of non-fulfillment of the task by ADF is determined for each k direction of the strike using each l range of altitudes of AAM. For this, the product of the affiliation functions $\mu(\delta_{\text{ud}kl})$ and $\varsigma(P_{\text{str}})$, which forms the affiliation function $\psi(S_{kl})$ is determined. In Fig. 1, the view of affiliation functions $\varsigma(P_{\text{str}k})$, $\mu(\delta_{\text{ud}kl})$, $\psi(S_{kl})$ is shown.

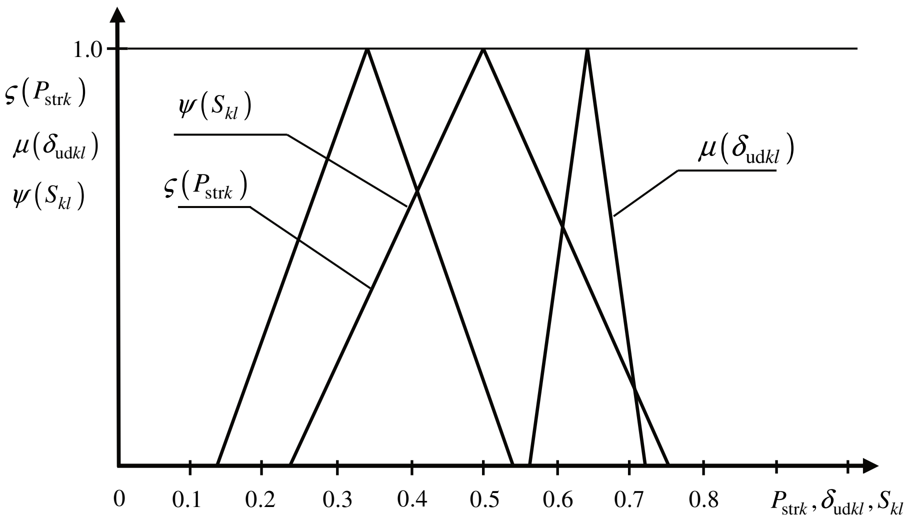

Fig. 1 View of affiliation functions $\varsigma(P_{\text{str}k})$, $\mu(\delta_{\text{ud}kl})$, $\psi(S_{kl})$

The triangular fuzzy numbers of the affiliation function $\psi(S_{kl})$ are determined by the formulas

$$\left.\begin{aligned} S_{kl}^{\min} &= \delta_{\mathrm{ud}kl}^{\min} P_{\mathrm{str}k}^{\min} \\ S_{kl}^{\mathrm{av}} &= \delta_{\mathrm{ud}kl}^{\mathrm{av}} P_{\mathrm{str}k}^{\mathrm{av}} \\ S_{kl}^{\max} &= \delta_{\mathrm{ud}kl}^{\max} P_{\mathrm{str}kl}^{\max} \end{aligned}\right\} \tag{6}$$

When assessing risk, the center of gravity of a fuzzy number C_{kl} of affiliation function $\psi(S_{kl})$ is used [12, 13]. The indicator C_{kl} is determined based on the equality of the planes that are divided by the center of gravity of the area of the triangle of the affiliation function $\psi(S_{kl})$ [13, 15]. This allows us to obtain a quadratic equation

$$2C_{kl}^2 - 4S_{kl}^{\max} C_{kl} + S_{kl}^{\max}\left(S_{kl}^{\min} + S_{kl}^{\mathrm{av}} + S_{kl}^{\max}\right) - S_{kl}^{\min} S_{kl}^{\mathrm{av}} = 0 \tag{7}$$

Hence, the center of gravity C_{kl} of the fuzzy number of the affiliation function $\psi(S_{kl})$ is determined by the formula

$$C_{kl} = S_{kl}^{\max} - \frac{\sqrt{16 S_{kl}^{\max 2} - 8\left[S_{kl}^{\max}\left(S_{kl}^{\min} + S_{kl}^{\mathrm{av}} + S_{kl}^{\max}\right) - S_{kl}^{\min} S_{kl}^{\mathrm{av}}\right]}}{4} \tag{8}$$

The task of ADF to protect assets is determined by the required number of destroyed targets from the strike $\delta_{\mathrm{des}}^{\mathrm{req}}$. Taking into account Eq. (2), the mathematical expectation of the relative number of AAM that are allowed to be undamaged

$$\delta_{\mathrm{ud}}^{\mathrm{all}} = 1 - \delta_{\mathrm{des}}^{\mathrm{req}} \tag{9}$$

The risk of non-fulfillment of the task by the ADF during the AAM strike from the k direction and using the l altitude range (R_{kl}) can be estimated as the degree of approximation of the center of gravity of a fuzzy number C_{kl} to the mathematical expectation of the relative number of targets that are allowed to be undamaged, and can be determined by the formula

$$R_{kl} = \frac{C_{kl} - \delta_{\mathrm{ud}}^{\mathrm{all}}}{\delta_{\mathrm{ud}}^{\mathrm{all}}} \tag{10}$$

At $C_{kl} = \delta_{\mathrm{ud}}^{\mathrm{all}}$ the risk $R_{kl} = 0$

Taking into account the probable use of the altitudes ranges by AAM, the risk of non-fulfillment of the task by ADF when striking from the k direction is equal to

$$R_k = \sum_{l=1}^{L} B_{lk} R_{kl} \tag{11}$$

Risk R_k can have a positive or negative value. A negative risk characterizes the certainty of the task fulfillment by the ADF, a positive one is the presence of prerequisites for the non-fulfillment of this task. Negative risk can vary from 0 to (−1.0), positive from 0 to (+1.0) and more.

The integrated (generalized) risk of non-fulfillment by ADF of the assets protection task from AAM strikes (R) is determined taking into account the importance of the directions of enemy's air strikes. To evaluate the coefficients of the importance of the enemy's air strikes direction, it is advisable to use the expert ranking method [16, 17]. Experts should arrange the directions in the order of their importance and

DOI 10.3849/aimt.01885

assign the number of the natural series (rank) to each direction. The first rank is given to the most important (dangerous) direction; the last one is to the least important.

The coefficient characterizing the degree of the danger of hitting assets from k direction (Z_{kj}) (the importance of the direction) is determined by the formula [16]

$$Z_{kj} = 1 - \frac{r_{kj} - 1}{K} \quad j = \overline{1, m} \quad k = \overline{1, K} \tag{12}$$

where r_{kj} – the rank given by the j expert to k direction;
m – the number of experts.

The coefficient of importance of the direction is determined by the j expert

$$\omega_{kj} = \frac{Z_{kj}}{\sum_{j=1}^{m} Z_{kj}} \qquad \sum_{k=1}^{K} \omega_{kj} = 1 \tag{13}$$

With the same competence of experts, the coefficient of importance of the k direction (ω_k) is

$$\omega_k = \frac{1}{m} \sum_{j=1}^{m} \omega_{kj} \tag{14}$$

When the competence of the j expert is evaluated by the coefficient ζ_j, $\sum_{i=1}^{m} \zeta_j = 1$, then

$$\omega_k = \sum_{j=1}^{m} \zeta_j \omega_{kj} \tag{15}$$

Integrated risk is determined by the formula

$$R = \sum_{j=1}^{K} \omega_k R_k \tag{16}$$

When making decisions regarding the organization of the air defense of the assets, it is advisable to take into account the criteria listed in Tab. 1 [18].

Tab. 1 Criterion risk intervals

Risk	**Linguistic characteristics**				
	Very low	Low	Average	High	Very high
Positive	0.00-0.19	0.20-0.39	0.40-0.59	0.60-0.79	≥0.80
Negative	0.00-(–0.19)	(–0.20)-(–0.39)	(–0.40)-(–0.59)	(–0.60)-(–0.79)	(–0.80)-(–1.00)

The above criteria are used in the assessment of both integrated risk and the risks in the direction of the strikes by AAM on the assets protected by the ADF.

A very high negative risk indicates complete confidence in the task fulfillment by ADF. At the same time, the composition of ADF can be excessive.

A positive risk that is higher than low indicates that it is necessary to implement measures to strengthen the AD of assets. For this purpose, AD units can be redeployed from directions where the negative risk is higher than average.

The block diagram of the methodology for determining the ADF risks of the task of assets protection from AAM strikes not being fulfilled is shown in Fig. 2.

According to the given methodology, the risk of non-fulfillment of the task of assets protection from AAM strikes is determined based on evaluating the effectiveness of the use of ADF in conditions of uncertainty of the enemy's actions. The results of determining the risk of non-fulfillment of the task by the ADF should be taken into account in conjunction with the results of the evaluation of their effectiveness in assets protection. It will increase the validity of decision-making during the organization of their AD.

The proposed method of determining the risks of non-fulfillment of assets protection by ADF is distinguished by taking into account the uncertainty of the direction of strikes, the altitudes of use of the AAM by the enemy, their density in the strike, which determines its novelty.

The application of the method is considered on the example of assets protection from the strikes of the air attack means with two six-channel short-range AD systems and four one-channel short-range AD systems. During the assessment of the situation, it was determined that the enemy can strike the asset from three directions ($K = 3$), use 45-60 air attack means; the time of the strike is 10-15 min. During the strike, the enemy can use four altitude ranges ($L = 3$): extremely small ($l = 1$), small ($l = 2$), medium ($l = 3$), large ($l = 4$). The given effectiveness of strike reflection is $\delta_{\text{des}}^{\text{rec}} = 0.7$. The minimum and maximum densities of air attack means in the strike are: $\lambda_{\min} = \frac{45}{15} = 3$ targ/min $\lambda_{\max} = \frac{60}{10} = 6$ targ/min

Normalized minimum density of AAM in the strike is $\lambda^{*}_{\min} = 0.5$.

In Tab. 2, the results of calculating coefficients of the direction importance of the AAM strike, the determination of triangular fuzzy numbers of the affiliation function of the degree of the enemy's use of these directions, and the probability of using the altitudes ranges by AAM are shown.

Tab. 2 Importance coefficients, triangular fuzzy numbers of strike directions, probabilities of using altitude ranges by AAM

The direction of AAM strike, k	Coefficient of importance, ω_k	Linguistic variable	Triangular fuzzy numbers			Probabilities of using altitudes ranges			
			$P_{\text{str}k}^{\min}$	$P_{\text{str}k}^{\text{av}}$	$P_{\text{str}k}^{\max}$	B_{1k}	B_{2k}	B_{3k}	B_{4k}
1	0.35	*C*	0.25	0.50	0.75	0.15	0.35	0.45	0.05
2	0.40	*B*	0.50	0.75	1.00	0.20	0.30	0.40	0.10
3	0.25	*H*	0	0.25	0.50	0.09	0.52	0.35	0.04

Taking into account the dependencies (5), the triangular fuzzy normalized densities of AAM in the strike for linguistic variables correspond to: very low (0.50; 0.50; 0.625); low (0.50; 0.625; 0.75); average (0.625; 0.75; 0.875); high (0.75; 0.875; 1.00); very high (0.875; 1.00; 1.00).

DOI 10.3849/aimt.01885

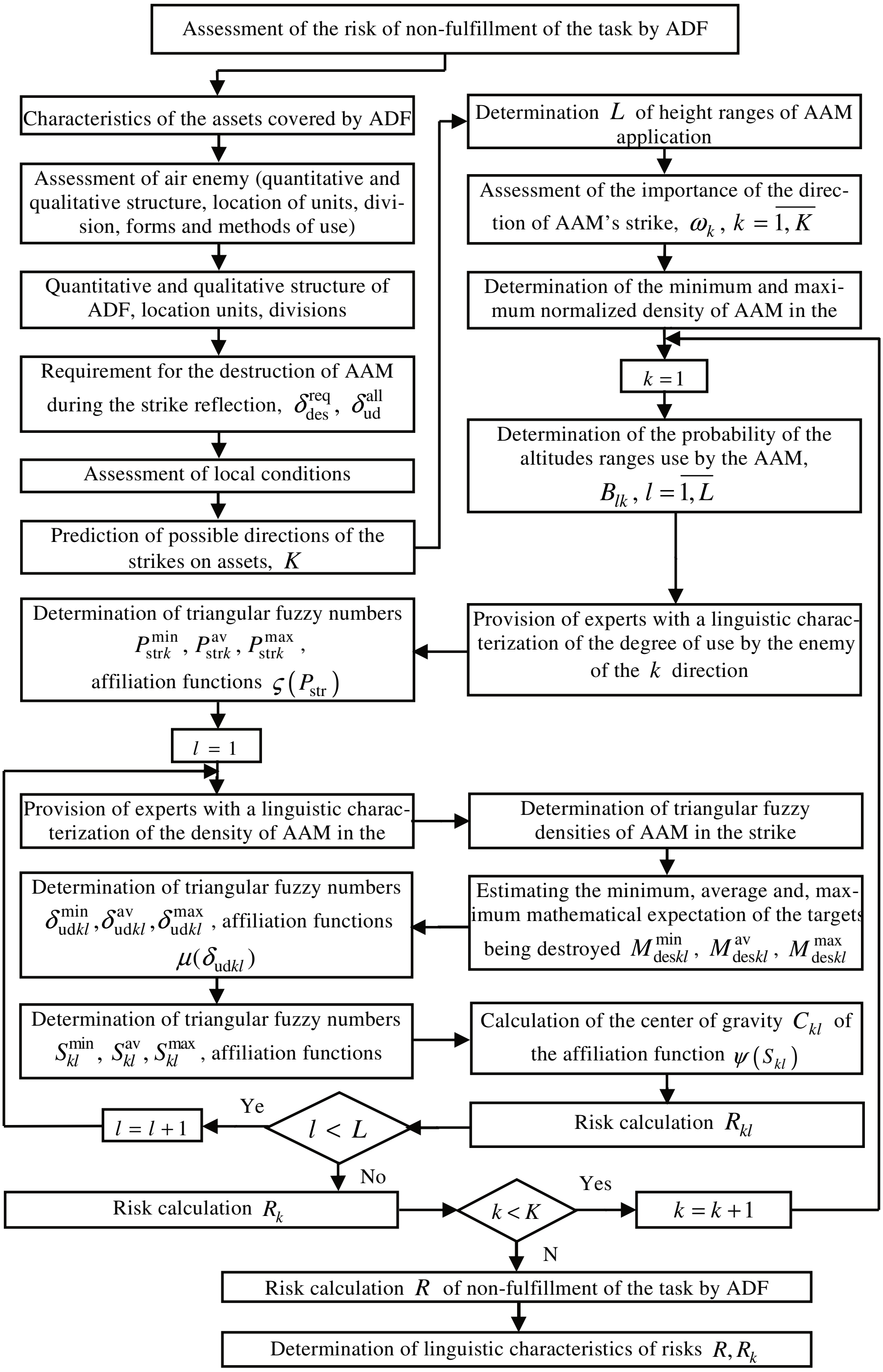

Fig. 2 Block diagram of methodology for determining risks of non-fulfillment by ADF of task of assets protection from strikes of AAM

Analytical-stochastic models [4, 5] are used to evaluate the combat effectiveness of air defense forces. The determination of the mathematical expectations of the number of destroyed AAM $M_{\text{des}}^{\min}$, $M_{\text{des}}^{\text{av}}$, $M_{\text{des}}^{\max}$, was carried out for fuzzy normalized densities of AAM, taking into account their average number in the strike. Triangular fuzzy numbers $\delta_{\text{ud}kl}^{\min}$, $\delta_{\text{ud}kl}^{\text{av}}$, $\delta_{\text{ud}kl}^{\max}$ and affiliation functions $\mu(\delta_{\text{ud}kl})$ were determined by the Eq. (2). The results of determining triangular fuzzy numbers of affiliation functions $\nu(\lambda^*_{kl})$, $\mu(\delta_{\text{ud}kl})$ are given in Tab. 3.

Tab. 3 Triangular fuzzy numbers of affiliation functions (λ^*_{kl}), $\mu(\delta_{udkl})$

Direction of the ADM	Altitude range	Linguistic variable	$\nu\left(\lambda_{kl}^*\right)$			$\mu\left(\delta_{\text{ud}kl}\right)$		
k	l		$\lambda_{kl}^{*\min}$	$\lambda_{kl}^{*\text{av}}$	$\lambda_{kl}^{*\max}$	$\delta_{\text{ud}kl}^{\min}$	$\delta_{\text{ud}kl}^{\text{av}}$	$\delta_{\text{ud}kl}^{\max}$
1	1	VL	0.500	0.500	0.625	0.66	0.75	0.82
	2	AV	0.625	0.750	0.875	0.58	0.68	0.75
	3	H	0.750	0.875	1.000	0.52	0.60	0.69
	4	L	0.500	0.625	0.750	0.55	0.64	0.72
2	1	L	0.500	0.625	0.750	0.22	0.35	0.51
	2	VH	0.875	1.000	1.000	0.16	0.28	0.46
	3	L	0.750	0.875	1.000	0.15	0.26	0.42
	4	VL	0.500	0.500	0.625	0.21	0.30	0.48
3	1	VL	0.500	0.500	0.625	0.45	0.65	0.82
	2	H	0.750	0.875	1.000	0.43	0.61	0.78
	3	AV	0.625	0.750	0.875	0.38	0.55	0.71
	4	L	0.500	0.625	0.750	0.40	0.60	0.73

Triangular fuzzy numbers of the affiliation function of the product $\psi(S_{kl})$ are determined by Eq. (6). The results of the calculation of the risks of non-fulfillment of the task by the air defense forces are given in Tab. 4.

A very low negative integrated risk $R = -0.138$ indicates some confidence in the sufficiency of air defense forces for assets protection from the strikes of air attack means with the given effectiveness. A significant (average) negative risk of non-fulfillment of the task by ADF for the third direction of AAM $R_3 = -0.435$ is determined by the experts' provision of a low degree of this direction use by the enemy. The positive risk for the first direction $R_1 = 0.123$ indicates a very low risk of non-fulfillment of the task by ADF with the required efficiency.

The obtained risks allow, along with the results of the efficiency assessment, to characterize more reasonably the reliability of the assets protection by ADF against AAM predicted strike.

Tab. 4 Risks of non-fulfillment of task by air defense forces

Direction of the ADM strike, k	Altitude range, l	$\psi(S_{kl})$			Center of gravity, C_{kl}	Risks		
		$S_{kl}^{\min}$	S_{kl}^{av}	$S_{kl}^{\max}$		R_{kl}	R_k	R
1	1	0.165	0.375	0.645	0.390	0.301	0.123	–0.138
	2	0.145	0.340	0.562	0.347	0.156		
	3	0.130	0.300	0.517	0.312	0.040		
	4	0.137	0.320	0.540	0.329	0.098		
2	1	0.110	0.262	0.510	0.287	–0.042	–0.182	
	2	0.080	0.210	0.460	0.242	–0.193		
	3	0.075	0.195	0.420	0.223	–0.256		
	4	0.105	0.225	0.480	0.261	–0.129		
3	1	0	0.162	0.410	0.184	–0.386	–0.435	
	2	0	0.152	0.390	0.174	–0.418		
	3	0	0.137	0.355	0.158	–0.472		
	4	0	0.150	0.365	0.167	–0.443		

4 Conclusions

Based on the use of fuzzy-multiple approach, a methodology was developed for determining the risks of non-fulfillment of the task by the ADF to protect assets from the AAM strike. The task of ADF is characterized by necessary mathematical expectation of the number of AAMs from the composition of the strike, which are destroyed during the strike repulsion. The methodology takes into account the uncertainties of the enemy's air strike directions on the assets, the use of air attack means' altitudes, their density in the strike, which is described by triangular affiliation functions. The methodology makes it possible to assess the integrated risk of non-fulfillment of the task by ADF and the risks for the predicted directions of the AAM strike on assets.

A direction for further research could be the determination of the risks of non-fulfillment of the task by the ADF, which are characterized by the required probability of preserving assets from the enemy's air strike.

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