# COMPARATIVE ANALYSIS OF GROUND-BASED AIR DEFENCE SYSTEM CAPABILITIES: JAMMING AND MANEUVERING

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***Abstract:*** *Nowadays, the vertical component of war, continuously subjected to in-depth analyses concerning its development and represented by two different system types – Aerial and Air Defence – is (and will be in the future) the decisive element of victory. Due to the assiduous development of this component, the physiognomy of war will be reshaped, with a higher weight on its vertical dimension, as opposed to the military actions conducted in the other traditional environments: terrestrial or maritime.*

***Keywords:*** *Surface-to-Air Missile System (SAMS), GBAD combat capabilities, jamming and maneuvering*

## 1. INTRODUCTION

Long Range Surface-to-Air Missile Systems, represents one of the basic pillars of airspace defence. This component of Air Defence was first mentioned in 1931, by the time Dr Gustav Rasmus presented the concept of Surface-to-Air Missile System (SAMS) at a scientific conference. World War II was the main reason to enhance and develop these systems. This development process assured the interoperability support within transport aviation, research, hunting, bombing but also with other categories of forces (army and naval), in order to ensure the airspace protection.

In the paper, we proposed ourself to analyse the SAMS combat capabilities, focusing on determining the possibilities of annihilation in case of an enemy usage of jamming and manoeuvring.

We have chosen this topic because the analysed elements are in accordance with the modern battlefield requirements and, at the same time, it is a material that can arouse the curiosity of the military, especially those who frame the missiles and anti-aircraft artillery.

Kill probabilities study, combined with the efficient exploitation of the technical and tactical characteristics of SAMS, is essential to obtain a high effectiveness against the aerial threat.

The main task of this paper represents the conduction of a study based on detailed analysis of the SAMS' kill probabilities, as well as their calculation, given the use of electronic jamming and manoeuvring by the enemy.

The three chosen systems for this study are $SAMS_1$ that belong to NATO, and $SAMS_2$, and $SAMS_3$ that belong to Russian Federation.

For the comparative analysis of technical and tactical SAMS' performances, the determination of $S_1$ $S_2$ and $S_3$' power index and determining of the aerial enemy kill probabilities in the conditions of use of jamming and manoeuvring, we used the AHP (Analytic Hierarchy Process) method.

By using this method, we can determine which is the most important characteristic (possibility of detection, kill probability, the mobility and possibility of jamming counter measures). After calculating the weights of the features in the Microsoft Excel programming environment, we represented the hierarchical results.

## 2. DETERMINING THE POSSIBILITIES OF ENEMY AIR TARGET ANNIHILATION BY JAMMING AND MANEUVRING. A CASE STUDY

### 2.1 Hierarchical analysis of the detection possibility, the kill probability, mobility and the electronic counter-countermeasure capability

In modern conflicts, in addition to the possibilities of research, detection, recognition and tracking of aerial targets, combined with the annihilation probabilities and the possibilities of manoeuvring troops and equipment, an important role belongs to the countermeasures for jamming. In this perspective, the diagram in figure 1 exemplifies the types of jamming used in recent military conflicts.

Active and passive jamming systems block the enemy's signals, as a result they are unable to fire against the target and react to sudden changes in the situation.

As a result of these challenges, some protection measures are required against various types of jamming (active, passive, radiolocation, thermal, television and visual-optical means of detecting and orienting the weapon to the potential enemy. [6]

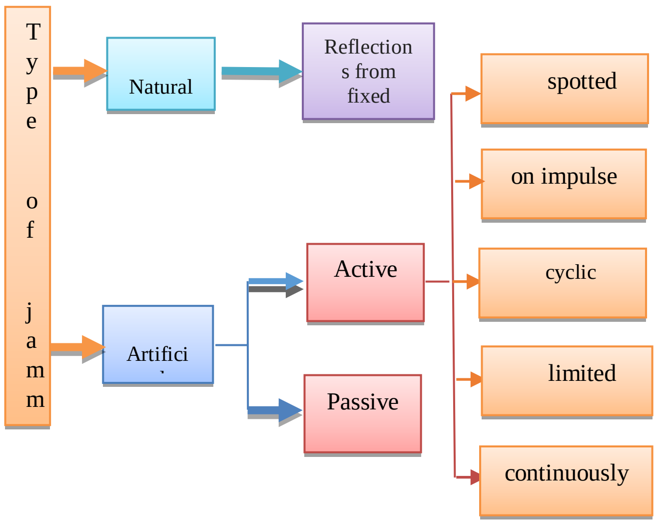


**FIG. 1** Jamming classification [6]

In order to highlight the importance of the 4 factors that decisively contribute to fulfilling the mission (the possibilities of research, detection, recognition and pursuit of targets, kill probability, possibilities of troops and equipment manoeuvring and electronic counter-countermeasures) we used a multi-criteria decision-making method, named AHP (Analytic Hierarchy Process).

This method is effective in making a complex decision. It can be useful in setting priorities to choose the most appropriate option.

This is done by reducing complex decisions to a sequence of pairwise comparisons, and then synthesizing the results. Therefore, the AHP concerns both the subjective and the objective aspects of a decision. At the same time, AHP incorporates a useful technique for verifying the consistency of the assessments regarding the decision factor.

Using this method, the weights for each evaluation criterion can be generated according to the decision factor by comparing the criteria in pairs. The overall score for a given option is a weighted sum of the scores for all criteria.

The AHP method involves the following steps:

- the evaluation development of each alternative decision for each criterion, by:
  - development of a pair comparison matrix, type m × m, where m is the number of evaluation considered criteria;
  - the normalization of the resulted matrix;
  - calculating the average value from each row to obtain the corresponding result;
  - calculation and verification of consistency ratio.
- the criteria weights elaboration.
- calculating the weighted average for each alternative decision.

Assuming that *the number of evaluation criteria* is *m* and the number of *evaluated options* is *n*, the steps of the analysis will be described in detail below.

To determine the weights for different criteria, the hierarchical analytical process begins with building a matrix (denoted by *A*) for pair comparison. This is of the type m × m, where *m* represents the number of criteria to be evaluated.

The terms in matrix *A* are constructed in coherent pairs. On the other hand, ranking can generally be done with small inconsistencies, which do not cause serious difficulties for AHP.

The hierarchy of components is achieved by building the matrix, which compares the performance indicators with each other. The performance indicators being detailed by criteria, the pair comparisons are repeated for each of the levels of this hierarchy, and the intensity of importance is evaluated using a Saaty scale. [9]

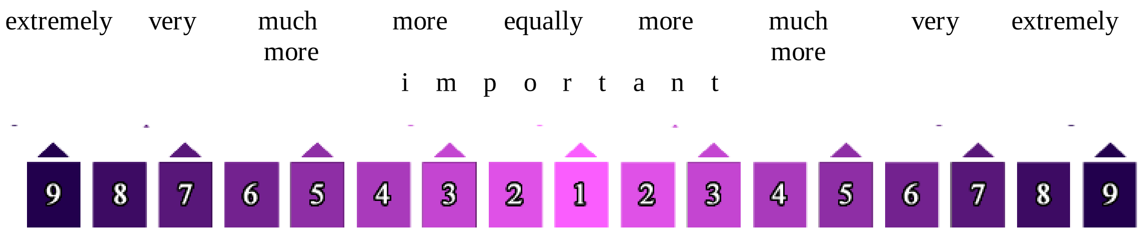


**FIG. 2** Saaty scale

This scale is structured on nine levels: basic (1 - equally important; 3 - more important; 5 - much more important; 7 - very important; 9 - extremely important and intermediate (2, 4, 6, 8 - when a compromise is needed) [9]

We applied this method in order to find out what is the most important feature of a Surface-to-Air Missile system. For this I have noted the characteristics which will have to be compared with $C_1$, $C_2$, $C_3$, $C_4$, where:

- $C_1$ = possibilities of detection ($P_d$);
- $C_2$ = kill probability ($K_p$);
- $C_3$ = mobility (M);
- $C_4$ = electronic counter-countermeasures ($E_{CCM}$)

If one of the chosen criteria is stronger (weaker) than the other, it’s value is set on the chosen scale, to the left (right).

*Table 1. Comparison of criteria*

| | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **$C_1$** | | | | | | | | | | | | | | | | | | **$C_2$** |
| **$C_1$** | | | | | | | | | | | | | | | | | | **$C_3$** |
| **$C_1$** | | | | | | | | | | | | | | | | | | **$C_4$** |
| **$C_2$** | | | | | | | | | | | | | | | | | | **$C_3$** |
| **$C_2$** | | | | | | | | | | | | | | | | | | **$C_4$** |
| **$C_3$** | | | | | | | | | | | | | | | | | | **$C_4$** |

The next step is to build the matrix corresponding to the pairwise comparisons. It will consist of 4 rows and 4 columns and will be marked with A, and the main diagonal contains only elements with the value of 1, according to the statement that each criterion is as important as itself.

What needs to be done next is to complete the upper triangle corresponding to the matrix. For this, two obvious rules must be followed (minding that when completing the rows of the matrix, we will compare the characteristics $C_i$ with $C_{i+p}$, where *i* is the line index of the matrix):

a. If the assigned value ($a_{i,i+p} \in \overline{1,9}$) is to the left of 1 (see table 1),this means that $C_i$ is superior to $C_{i+p}$, so this value is to be filled in the matrix.

b. If the assigned value ($a_{i,i+p} \in \overline{1,9}$) is located on the right side of 1 (see table 1), this means that $C_{i+p}$ is higher than $C_i$, so that the value $\frac{1}{a_{i,i+p}}$ is completed in the matrix. We have represented below the matrices, fractional and decimal.

$$A = \begin{pmatrix} 1 & \frac{1}{3} & 3 & \frac{1}{2} \\ 3 & 1 & 2 & 5 \\ \frac{1}{3} & \frac{1}{2} & 1 & \frac{1}{5} \\ 2 & \frac{1}{5} & 5 & 1 \end{pmatrix} \qquad A \begin{pmatrix} 1 & 0.33 & 3 & 0.5 \\ 3 & 1 & 2 & 5 \\ 0.33 & 0.5 & 1 & 0.2 \\ 2 & 0.2 & 5 & 1 \end{pmatrix}$$

In the following, we will calculate the eigenvector according to Saaty's theory, this being in fact the normalized eigenvector of the matrix. To better understand, it is necessary to recapitulate the notions of eigenvalue and eigenvector, associated with a quadratic matrix.

Therefore, if *X* is a column vector of size *n* different from 0 and *A* is a matrix of type *n x n*, then AX is another column vector Y, of size *n*, resulted from their multiplication, according to the multiplication rule of matrices.

$$A_{n,n} \cdot X_{n,1} = Y_{n,1} \tag{2.1}$$

If the vectors X and Y are collinear, which means the condition $Y = \lambda \cdot X$, is satisfied: then X is called the eigenvector and λ eigenvalue of the matrix A, considering λ a scalar (complex or real, provided that the elements of the matrix are either complex or real).

Therefore, it follows that the equation that characterises eigenvalues and vectors is:

$$A \cdot X = \lambda \cdot X; \tag{2.2}$$

where X is different from zero

The solutions of the equation are represented by the eigenvalues $\lambda_1, \lambda_2, ..., \lambda_n$, and then the corresponding eigenvectors $X_1$, $X_2$, …, $X_n$. Equation 2.2 is written as:

$$(A - \lambda \cdot I_n) \cdot X = O_n, \tag{2.3}$$

where $I_n$ is the unit matrix, and $O_n$ is the null matrix, of type *n x n.*

As mentioned before, X is a nonzero eigenvector, therefore it is clear that the equation (2/3) can be satisfied only if the matrix $A - \lambda \cdot I_n$ has the determinant equal to zero:

$$\det(A - \lambda \cdot I_n) = 0 \tag{2.4}$$

In this way, a *n* degree algebraic equation was obtained, which is called *the characteristic equation of the matrix A*, with the unknown $\lambda$. It follows that the solutions the equation (2.4) are the eigenvalues of the matrix.

Then in equation (2.3) the eigenvalues resulted from the calculation are replaced and result the eigenvector values, corresponding to each eigenvalue.

Observation is required:

By replacing the eigenvalues $\lambda_k$ in (2.3) it is necessary to solve a homogeneous system of equations (it has zero free terms), which has the determinant, obviously, zero (this is the term from the left of the equation (2.3), and $\lambda_k$ represents one of the solutions of the equation (2.4).

It can be stated that the specified homogeneous system will not have a unique solution, namely the eigenvector $X_k$ cannot be uniquely determined. Moreover, this conclusion could be extracted from the qualitative analysis of the equation (2.2), it obviously being that if X is the solution, therefore the vector kX will also verify equation (2.2), where k is a real or complex scalar (according to the elements of the matrix A).

We`ll consider that the eigenvector, one of the representative sets of homogeneous system solutions mentioned above, is suitable to values of the parameters on which it depends.

Usually, the obtained eigenvectors is normalized.

It is also proven that the solution of the homogeneous system depends on a number of parameters equal to the order of multiplicity of the respective eigenvalue, as a solution of the characteristic equation (2.4).

For example, a simple eigenvalue will correspond to an indefinite simple homogeneous system (its solution will depend on a parameter); a double eigenvalue will correspond to an indefinite double homogeneous system (its solution will depend on two parameters), etc. [8]

So, going back to the matrix above, it can be said that this is now a complete comparative matrix. The next step is to normalize the matrix, and this is done by summing the numbers on each column.

*Table 2. Column summation of matrix elements*

| Criteria | **$C_1$** | **$C_2$** | **$C_3$** | **$C_4$** |
|---|---|---|---|---|
| **$C_1$** | 1.00 | 0.33 | 3.00 | 0.50 |
| **$C_2$** | 3.00 | 1.00 | 2.00 | 5.00 |
| **$C_3$** | 0.33 | 0.50 | 1.00 | 0.20 |
| **$C_4$** | 2.00 | 0.20 | 5.00 | 1.00 |
| Total | 6.33 | 2.03 | 11.00 | 6.70 |

Next, each element in the matrix will be divided by the sum of the column to which it belongs, to obtain its normalized result.

$$a_{ij} \rightarrow \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \forall j = \overline{1, n}; (n = 4) \tag{2.5}$$

The normalized matrix results:

$$A = \begin{pmatrix} 0.16 & 0.16 & 0.27 & 0.07 \\ 0.47 & 0.49 & 0.18 & 0.75 \\ 0.05 & 0.25 & 0.09 & 0.03 \\ 0.32 & 0.1 & 0.45 & 0.15 \end{pmatrix}$$

The eigenvector will be represented by the average value of each line, divided by the number of established criteria (four).

$$w_{ij} = \frac{\sum_{j=1}^{n} a_{ij}}{n}, \forall i = \overline{1, n}; (n = 4) \tag{2.6}$$

According to normalized matrix we will calculate the eigenvector

*Table 3. Calculation of the eigenvector*

| | **$C_1$** | **$C_2$** | **$C_3$** | **$C_4$** | **Total** | **Average** |
|---|---|---|---|---|---|---|
| **$C_1$** | 0.16 | 0.16 | 0.27 | 0.07 | 0.67 | 0.167 |
| **$C_2$** | 0.47 | 0.49 | 0.18 | 0.75 | 1.89 | 0.473 |
| **$C_3$** | 0.05 | 0.25 | 0.09 | 0.03 | 0.42 | 0.105 |
| **$C_4$** | 0.32 | 0.10 | 0.45 | 0.15 | 1.02 | 0.254 |

$$\begin{pmatrix} 0.16 & 0.16 & 0.27 & 0.07 \\ 0.47 & 0.49 & 0.18 & 0.75 \\ 0.05 & 0.25 & 0.09 & 0.03 \\ 0.32 & 0.1 & 0.45 & 0.15 \end{pmatrix} \xrightarrow[\text{average rows}]{} W = \begin{pmatrix} 0.167 \\ 0.473 \\ 0.105 \\ 0.254 \end{pmatrix}$$

Thus, we obtained the value of the corresponding (normalized) vector

$$W_{\lambda} \begin{pmatrix} 0.17 \\ 0.47 \\ 0.11 \\ 0.25 \end{pmatrix}$$

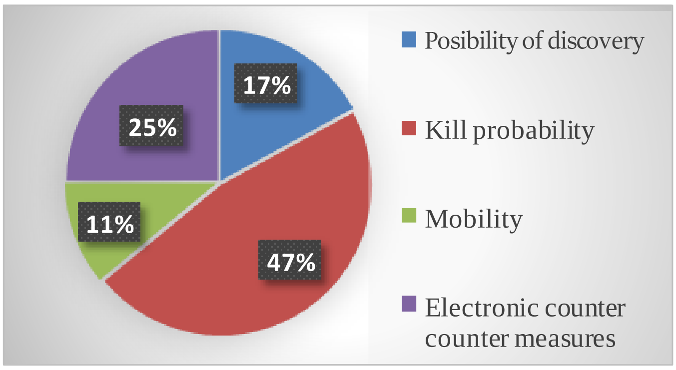


**FIG. 3** Criteria subjects to AHP analysis and their weights

From the diagram above it can be seen that the SAMS` kill probabilities $C_2$ has the largest share, consequently it is the most important feature.

Next, I will analyse regarding on the study consistency, meaning I will appreciate the consistency of the comparison matrix.

It can be stated about the comparative judgment that it has consistency if it respects the principle of transitivity, which is stated as follows: if *X* is more important than *Y*, and it is more important than *Z*, then obviously it follows that *X* is more important than the criterion *Z*.

By transforming these qualitative judgments into quantitative assessments, it results that it can stated, firstly, the consistency of a mutual matrix.

Thus, about a reciprocal matrix $\left(a_{ij} > 0; a_{ij} = \frac{1}{a_{ji}}\right)$ it can be stated that it is consistent if it satisfies the relation:

$a_{jk} \cdot a_{kp} = a_{jp}, \forall j,k,p$

Saaty's theorem is being demonstrated:

If the polynomial characteristic of a reciprocal matrix (of type *n x n*) is as follows: $P(\lambda) = \lambda^n - n \cdot \lambda^{n-1}$, it results that the matrix is consistent.

By this method, the eigenvalues of this type of matrix (solutions of the equation $P(\lambda) = 0$ will be zero (multiple root of *n - 1* times) and *n (*single root).

Therefore, the choice of both the eigenvector as a vector of priorities and the maximum eigenvalue is natural. At the same time, the study consistency can be appreciated by the difference $\lambda_{max} - n$. Normally, it should be zero.

However, it is quite unlikely to obtain a consistent comparison matrix from the comparisons between the analysed criteria, therefore, for the purpose of the above definition, the following consistency indicators (Saaty) were stated:

- Consistency index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (2.7)$$

- Random value of the consistency index (IR). It is obtained by randomly generating reciprocal matrices with values $\frac{1}{9}, \frac{1}{8}, \ldots, 1, \ldots, 8, 9$ and calculating the CI consistency index. Its average values are presented in table 5, for matrices of the type 3 x 3,…, 10 x 10.

*Table 4 Random values of the consistency index*

| N | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|
| RI | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

- The ratio (rate) of consistency is defined as equal to the ratio between the two indicators listed above:

$$CR = \frac{CI}{RI} \tag{2.8}$$

To find out the value of the consistency ratio, we have to follow the steps below which consists of:

1. Calculation of the consistency measure;
2. Calculation of the consistency index (CI);
3. Calculation of the consistency ratio (CR).

To calculate the *measure of consistency*, we can use the multiplication function of the matrix in Excel = MMULT (). In order to obtain this indicator, it will proceed as follows: multiply successively the values of the column „Total" (from table 4) with the sum of the weights obtained, and the result will be divided by the weight of the corresponding row.

Taking into account the calculation of the eigenvector it will result the *consistency measure*

Table 5 *Calculation of the consistency measure*

| | **$C_1$** | **$C_2$** | **$C_3$** | **$C_4$** | **Total** | **Average** | **Consistency measure** |
|---|---|---|---|---|---|---|---|
| **$C_1$** | 0.16 | 0.16 | 0.27 | 0.07 | 0.67 | 0.167 | 0.91 |
| **$C_2$** | 0.47 | 0.49 | 0.18 | 0.75 | 1.89 | 0.473 | 1.11 |
| **$C_3$** | 0.05 | 0.25 | 0.09 | 0.03 | 0.42 | 0.105 | 1.36 |
| **$C_4$** | 0.32 | 0.10 | 0.45 | 0.15 | 1.02 | 0.254 | 0.71 |

We are going to find out the values of the *consistency index* and *the consistency ratio*. For this it is necessary to find the maximum eigenvalue $\lambda_{max}$, which is calculated by dividing each of the values in the „Total" column by the values in the „ Average" column in table 6, and then the arithmetic average of the results is calculated.

Results:

$$\lambda_{max} = \frac{4{,}011 + 3{,}995 + 4 + 4{,}015}{4} = 4{,}00525$$

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{4{,}00525 - 4}{3} = 0{,}00175$$

$$CR = \frac{CI}{RI} = \frac{0.00175}{0{,}9} \cong 0{,}00194 < 0{,}1$$

Table 6. *Calculation of the consistency index / ratio*

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | Total | Average | Consistency measure |
|---|---|---|---|---|---|---|---|
| $C_1$ | 0.16 | 0.16 | 0.27 | 0.07 | 0.67 | 0.167 | 0.91 |
| $C_2$ | 0.47 | 0.49 | 0.18 | 0.75 | 1.89 | 0.473 | 1.11 |
| $C_3$ | 0.05 | 0.25 | 0.09 | 0.03 | 0.42 | 0.105 | 1.36 |
| $C_4$ | 0.32 | 0.10 | 0.45 | 0.15 | 1.02 | 0.254 | 0.71 |
| | | | | | | CI | 0.00175 |
| | | | | | | RI | 0.9 |
| | | | | | | **CR** | **0.00194** |

Analysis of this type is considered consistent if and only if $CR < 0.1$. Any higher value requires a re-examination of the made comparisons. As in our case the CR is less than 0.1, it is not necessary to re-examine the made comparisons.

**2.2 Calculation of the power index of SAMs $S_1$ $S_2$ and $S_3$**

Next, we will develop the previous study by determining *the power index* of the SAM $S_1$ $S_2$ and $S_3$.

The three SAMS power index calculation consists of the necessity of evaluation by requirements and capabilities of the $SAMS_1$ compared to the performance of $SAMS_2$ and $S_3$.

In the first phase, for this index determination, we will proceed as in the case of the multicriteria analysis method AHP (we choose the criteria for comparison and we calculate their weights, following the necessary steps).

In this perspective, I will not choose other criteria, or other weights, but I will also use those used in this chapter, where, by calculating their weights, I determined the importance of each criterion in the process of fighting against an aerial threat.

In order to achieve the criteria homogeneity (which can be described both quantitatively and qualitatively), we have built a performance scale with five levels (Table 7).

Table 7 *Presentation of criteria, weights and performance evaluation*

| Performance criteria | Weights | $SAMS_1$ | $SAMS_2$ | $SAMS_3$ |
|---|---|---|---|---|
| Possibilities of detection ($P_d$) | 0,167 | ≈ 160 km | ≈ 300 km | ≈ 400 km |
| Kill probabilities ($K_p$) | 0,473 | ≈ 0,8-0,9 | ≈ 0,8-0,91 | ≈ 0,8-0,93 |
| Mobility (M) | 0,105 | 50-60 km/h | 40-60 km/h | 25-60 km/h |
| Electronic counter-countermeasures ($E_{CCM}$) | 0,254 | high value | moderate | high value |

Table 8 *Performance scale*

| Level of performance | Scaling |
|---|---|
| Not applicable | 0.0 |
| Limited | 0.25 |
| Accepted | 0.5 |
| Significant | 0.75 |
| Remarkable | 1 |

The next step to determine the power index of SAMS is represented by the application the calculation formula:

$$WPI = P_d\, w_1 + k_p\, w_2 + M\, w_3 + E_{CCM}\, w_4 \tag{2.9}$$

The evaluation, integration of indicators / performance criteria of missile systems are presented in table 9.

Table 9 *The calculation of their power index*

| **Indicators (Performance criteria)** | **Weights ($W_i$)** | **$SAMS_1$** | **$SAMS_2$** | **$SAMS_3$** |
|---|---|---|---|---|
| Possibilities of detection (Pd) | 0,167 | 0,5 | 0,5 | 0,75 |
| Kill probabilities (Kp) | 0,473 | 0,75 | 0,75 | 0,75 |
| Mobility (M) | 0,105 | 1 | 0,75 | 0,75 |
| Electronic counter-countermeasures ($E_{CCM}$) | 0,254 | 1 | 0,75 | 1 |
| Weapon power index (WPI) | | 0,79725 | 0,7075 | 0,81 |

Following the performed analysis, according to the chosen criteria (possibility of detection, annihilation probabilities, mobility, possibility of jamming protection), it can be seen that the $SAMS_1$ has a second power index compared to the other systems, but if we make a parallel between the necessary working times regarding the maintenance works of the three systems, it can be stated that the $S_1$ version ranks above the level of the two Russian systems $S_2$ and $S_3$.

The $SAMS_2$ and $S_3$ subsystems, because they are built by Russian standards, they are not built with high-performance equipment for automatic testing, diagnosis, technique and fault signalling, which leads to increased service life maintenance.

## CONCLUSIONS

The evaluation of SAMS information is very important for the military personnel assigned to use the missile weapon and anti-aircraft artillery.

At the same time, putting into the practice this knowledge on the battlefield results an increased effectiveness against aerial threat.

Taking into account the report of the last decades regarding the evolution of Air Defence systems, it can be said that they have been considerably developed.

The implementations brought to the systems contributed on the one hand to increased capabilities of SAMS, and on the other hand to improved manoeuvre force capabilities.

The comparative analysis of SAMS, technical and tactical performances, was based on: evaluation of the chosen criteria (WPI, $IPA, P_d, K_p, M, J_{cm}$), calculation of their weights and their ranking according to importance.

This study was performed with multicriteria analysis of decision making, the AHP (Analytic Hierarchy Process) method.

After completing these steps, we have calculated the power index of the SAMS. The detailed study describes the notions used by this method of analysis, as well as the steps taken to calculate the weights of the chosen criteria. After following the steps, which consisted of calculations performed in the Microsoft Excel programming, we represented the results hierarchically.

According to the calculations made, we came to the conclusion that the possibility of destroying an air defence system has the greatest weight in the process of fighting an enemy target, and the power index and, at the same time, the chances of destroying aerial targets under the conditions of usage of jamming and manoeuvring on the $S_1$ are the second place compared to all three systems.

In conclusion, following the presented information, it can be stated that the SAMS have had a significant evolution in several directions (technological, structural and action-based) and along with their evolution gradually increasing their importance, becoming an indispensable element in the battlefield.

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