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Counting the Uncountable –Introduction to the New Method of Evaluation of the Efficiency of Air Defense

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Abstract

The aim of the research was to create such a calculation model for air defense efficiency that will enable us to determine the level of capabilities to complete tasks by air defense in combat conditions. The innovative approach to the efficiency of air defense presented in the article focuses on the methods and algorithms enabling the assessment of the feasibility of the air defense task. In its general form, it is based on the determination of the probable number of aerial threats intended for the implementation of an air task (destruction, disablement, disruption of the protection unit) and the possibility of air defense systems to repel an air attack. The research was conducted with the use of qualitative methods – when determining the elements of protection or tactical and technical data. The results of the presented research can be implemented in the military decision making process in air defense in tactical level of command.

Keywords: defense, efficiency, air defense, air threats, combat capabilities.

1. Introduction

The changing air safety environment (Radomyski et al., 2018), the growing importance of aviation in armed conflicts and the development of aerial threats (Kulik, 2020) necessitate the search for solutions aimed at increasing the ability to counteract air attacks. A. J. Wilson noticed that “studies such as these (on the development and enhancement of air defense capabilities – the author’s explanation) must address all the systems needed to collect information, facilitate its interpretation, aid subsequent decision making and take the necessary action” (Wilson, 1994). Current research focuses primarily on technological development such as radar systems, missile guidance (Wen, and Orlando 2020; Wand, Dong, 2013) and real-time decision support, also using artificial intelligence (Hocaoğlu, 2019; Baldwin, and Felder, 2019; Goztepe et al., 2015). In other words, the emphasis is given to the conduct of the air defense operations, while the entire decision-making process carried out by the armed forces along with the assessment (evaluation) of the adopted course of action (CoA) is marginalized.

For modern war in which an environment is uncertain and things are too complex to understand from only one aspect, the military decision making process (MDMP) eases the commander’s decision making (Snyder, 1989). According to FM-6-0, the MDMP is an iterative planning methodology for understanding the situation and mission, develop a course of action, and produce an operation plan or order (FM 6-0, 2014). Regardless of the differences in MDMP in various states one of the most common assumptions about decision making is that decisions should be as rational as possible “people make decisions by identifying and comparing options to determine which one produces the optimal outcome for a given set of circumstances” (Vasilescu, 2011). The assessment of the adopted CoA plays a special role in this respect, i.e. in the case of air defense, and the assessment of the efficiency of air defense.

The evaluation of the efficiency of air defense allows determining (within the limits of probability) whether the variant of action developed by the staff will accomplishment of the air defense mission (operation) – to protect the force and selected geopolitical assets from aerial attack, missile attack, and surveillance (FM 3-01-11, 2000). This is especially important in the case of a limited number of air defense systems, both locally and globally.

So far, the conclusions from the research conducted on the implementation of decision support systems such as AI in air defense clearly indicate that “data scientists might use not only AI techniques and technologies, but also other sciences to apply expertise in data preparation, statistics, and analysis to investigate complex problems” (Goztepe et al., 2015). Undoubtedly, determining the effectiveness of air defense is a complex problem, which is why we believe that conducting the evaluation of efficiency in a systematic and scientifically justified manner will allow for a more accurate formation of predictions with regard to the activities carried out and the development of the best possible decision during the implementation of the MDMP at the tactical level of operation. Therefore, the purpose of the research on the effectiveness of the air defense described in this article was to create a calculation model (algorithm) that would enable the determination of the level of task completion by units and sub-units of air defense in combat conditions.

When developing a new method of calculating effectiveness, the authors used the so-called "effective theory", designed to model a certain observed phenomenon (in this case, the efficiency of air defense) without describing the underlying processes in detail. Such a theory predicts behavior with moderate success because decisions are often irrational and based on a wrong analysis of the consequences of a choice. In particular, considering the possibility of modeling or predicting decisions from the perspective of an armed conflict, where "surprise" is one of the basic principles of warfare. Moreover, due to cognitive, time and technical limitations, the observer is frequently not able to describe the observed phenomenon precisely or the information obtained is incomplete. The most famous astrophysicist of our time, Stephen Hawking, explained the use of effective theory in physics, "...we are not able, for example, to strictly solve the equations describing the gravitational interaction of every atom of the human body with every atom of the globe. But for practical purposes, a few numbers are enough to describe the force of gravity (...). " Therefore, it should be kept in mind that the proposed solution for calculating the efficiency of air defense is to some extent a generalization. It is impossible to describe all the dependencies related to the concept of air defense efficiency with a mathematical formula. During the research process, over 100 variables influencing the effectiveness of air defense were distinguished. However, in order to simplify the process, it was decided to include the most important of them based primarily on the opinion of experts.

2. Literature and methods

Despite the fact that the efficiency of air defense is a very important factor helping to assess the feasibility of a task, the vast majority of research in the early twenty-first century was fragmentary. As a result of the analysis of their content, it can be concluded that they propose various qualitative and quantitative methods of determining efficiency. Most often, however, they are detached from the command process carried out at command posts at the tactical and operational level. One of the few publications in which the procedure algorithm determining the effectiveness was presented is the use of "techniques to assess the modernization needs of the military". The solution (method) presented in it allows us to calculate the efficiency of the particular air defense measures performing the task of covering. Its drawback, however, is that it lacks detailed information on the values (indicators) adopted for the calculations (Kacer, and Májek, 2006). In the case of other publications, it can be seen that the efficiency of air defense is defined as the ratio between the reduced potential of the aerial threats obtained thanks to the activity of the anti-aircraft defense forces and the total of this potential (Kazakhov, 2010). These studies also lack the basic information relating to the method of determining the potential, which makes the entire methodology of determining the efficiency difficult to verify from the point of view of the correctness of the assumptions adopted and the possibility of their implementation (Tsyrndorzhiyev, 2012).

Yet another publication proposes the adoption and use of a SWOT analysis for evaluating efficiency, especially at command level (Şandru, 2016). It should be noted that this method is one of the most popular in strategic management of an organization. However, despite the many advantages of SWOT, it also has certain disadvantages. This applies to subjectivism in assessing the efficiency of air defense without taking into account the detailed data on the aerial threats. In this situation, the assessment of air defense may vary despite the same input data and tactical situation and its results will be heavily dependent on the knowledge and experience of the assessor, which may be quite varied.

Another option adopted in evaluating the efficiency of air defense is the use of computer simulation techniques (Zdrodowski, 2003). In this regard, it should be noted that when acting in the conditions of combat operations with limited planning time, during which variants of the operation of the enemy and his own troops are being developed, the commander of the air defense unit (subunit) may not be able to conduct a computer simulation. In addition, it should also be emphasized that the simulation result is largely dependent on the prepared input databases and also the mathematical formulas used to determine the probability of target destruction.

For many years, the Polish Armed Forces used programs supporting the process of calculating the effectiveness of air defense. They were based on the number of areal threats in the operation, the number simultaneous engagement capability and the so-called fire units used by the air defense unit (sub-unit). The following formula was used to calculate the efficiency of the air defense:

$$E_{AD} = \frac{\sum_{i=1}^{n} K_i * N_{ADSi} * J_i * R_i}{N_s} * 100\% \quad (1)$$

Where:

E_{AD} – efficiency of air defense;
K_i – general coefficient for particular types of air defense (anti-aircraft) means;
N_{ADSi} – the number of capabilities to simultaneous engagement of multiple targets of AD systems (sub-units), capable of destroying a target on its own with a certain probability, in one firing cycle;
Ji – number of missiles (ammunition) available for i-th type of equipment;
Ri – the coefficient taking into account the number of interactions of the i-th type of equipment, in one firing cycle.

In another variant, the efficiency was calculated on the basis of the number of aircrafts involved in the raid (attack), the raid duration, the number of simultaneous engagement capability and the fire unit provided for a given anti-aircraft system. The following formula was used for this purpose:

$$E_{AD} = \frac{\sum_{i=1}^{n} K_i * N_{ADSi} * \left(\frac{C}{Y} \cdot \frac{T_n}{T_C}\right) * P_i}{N_s} * 100\% \quad (2)$$

Where:

E_{AD} – efficiency of air defense;
Ki – general coefficient for particular types of air defense (anti-aircraft) system;
N_{ADSi} – the number of capabilities to simultaneous engagement of multiple targets of AD systems (sub-units), capable of destroying a target on its own with a certain probability, in one firing cycle;
Pi – the probability of hitting an air target with a certain number of missiles (ammunition) without taking into account the impact of interference'
C – the number of missiles (ammunition) for a given type of firearms of the air (anti-aircraft) defense;
Y – the estimated average number of missiles (ammunition) used to destroy;
Tn – duration of the raid;
Tc – duration of a firing cycle for the given type of AD system.

In the next variant, it was possible to calculate the air defense efficiency on the basis of the number of air threats in the raid, the duration of the raid, the spatial impact conditions, the number of firing channels and the firing units. The following formula was used for this purpose

$$E_{AD} = \frac{\sum_{i=1}^{n} K_{PUi} * K_i * N_{ADSi} \left(\frac{C}{Y} \cdot \frac{T_n}{T_C}\right) * P_i}{N_s} * 100\% \quad (3)$$

Where:

E_{AD} – efficiency of air defense;
K_{PUi} – the spatial contribution coefficient for particular types of air defense system;
Ki – general coefficient for particular types of air defense (anti-aircraft) system;
N_{ADSi} – the number of capabilities to simultaneous engagement of multiple targets of AD systems (sub-units), capable of destroying a target on its own with a certain probability, in one firing cycle;
Pi – the probability of hitting an air target with a certain number of missiles (ammunition);
C – the number of missiles (ammunition) for a given type of firearms of the air (anti-aircraft) defense;
Y – the estimated average number of missiles (ammunition) used to destroy the target;
Tn – duration of the raid;
Tc – duration of a firing cycle for the given type of AD system.

Based on the presented examples (variants) of the calculation of the air defense efficiency, it can be noticed that it depends to a large extent on the coefficients adopted when calculating the value of the expected number of destroyed aerial threats. On this basis, it can be concluded that the model for calculating the air defense efficiency will be the more precise, the more precisely the coefficients used in it are selected. Therefore, an attempt was made to define a new methodology where the selection of coefficients will be firstly optimal, and secondly will correspond to the actual, real parameters of individual components on the modern battlefield.

The presented research is the result of a two-year research work carried out under a research grant financed by the MoD. The research team consisted of four pilots, four specialists in the field of air defense and representatives of air defense support units such as radio engineering troops. Moreover, representatives of the commands and staffs of the Air Defense units and the Air Force of the Polish Armed Forces were invited to participate in the qualitative research.

3. Efficiency of air defense

For the purpose of quantifying the efficiency of aid defense, it is reasonable to use efficiency coefficients that should be: representative, sensitive, simple, systemic and stochastic (Zdrodowski, 2003). The representativeness of the indicator means that it should quantify the degree of performance of the task (achievement of the goal) by the air defense.

1. The sensitivity of the coefficient should be understood as its sensitivity to changes in parameters relevant to the implemented air defense task.
2. Simplicity means that it only includes parameters relevant to the purpose of the air defense. Secondary parameters are omitted here, as they can only complicate the evaluation without increasing the precision of the results.
3. The systemic character consists in selecting the coefficient in such a way that it takes into account the influence of all important factors determining the combat operations of the air defense.

The occurrence of random factors, which is characteristic of the air defense system, is reflected in random variables and determines that the combat efficiency indicator itself - as a function of random variables - is also a random variable, too. For this reason, the value of the efficiency index is most often directly related to the average (expected) value of the aerial threats destroyed by the air defense.

The general formula for calculating the efficiency of air defense systems was thus defined as the quotient of the air defense capabilities, expressed as the expected number of enemy aerial threats destroyed to the expected number of enemy aircrafts operating on the area of operation.

$$E_{AD} = \frac{M_{AD}}{N_{EA}} * 100\% \qquad (4)$$

Where:

EAD – efficiency index (in %);

MAD – air defense capabilities, demonstrated by the average (expected) number of the enemy's destroyed aerial threats;

NEA – the number of enemy aircraft affecting the covered troops (facilities).

The above formula shows that the air defense combat efficiency index is such a numerical characteristic that determines the degree of adaptation of the air defense system to the implementation of the tasks assigned to it. For this reason, the value of the efficiency index is most often directly related to the average (expected) number of the enemy's destroyed aerial threats.

Formula (4) shows that EAD = f (MAD) should be proportional and linear, i.e. each increase in the combat potential of the air defense should be accompanied by a steady increase in the air defense combat efficiency index, as shown in the figure below.

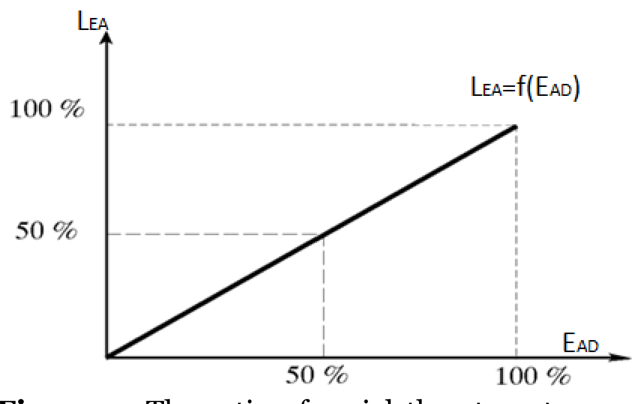

Figure 1. The ratio of aerial threats not performing any tasks (LEA) to the efficiency of air defense (EAD), Adopted from: "Obrona powietrzna" by Zdrodowski et al. p. 29. Copyright 1996, by AON.

The adoption of such assumptions, however, leads to the erroneous conclusion that in order to fully achieve the goal of the air defense in opposing one strike, it is necessary to destroy 100% of the aerial threats affecting the covered troops (facilities). In this regard, it should be noted that this conclusion will be appropriate in a situation where the attack will be carried out only by unmanned aerial systems (UAVs, cruise missiles), which will be characterized by complete remotely or automation of navigation and pilotage. The figure below this situation is represented by the ratio for UAVs.

At this point, it should be noted that assuming that the enemy is conducting an air attack against protected assets only with the use of unmanned aerial and missile threats (ballistic missiles, cruise missiles or unmanned aerial vehicles), there will be no impact on the so-called human factor (pilots and crew).

However, in other situations where there is at least a partial human participation this relationship will change Lea = f (EAD) according to the trajectories shown in the figure for attacks carried out by manned aircrafts and in the mixed formula (manned and unmanned).

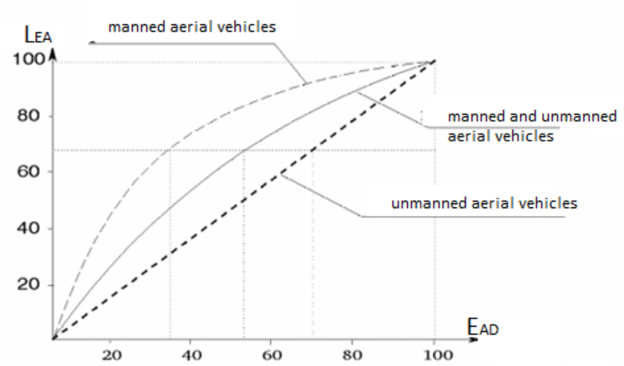

Figure 2. Ratio of LEA = f (EAD) in the contemporary circumstances; Adopted from: "Obrona powietrzna" by B. Zdrodowski et al., p. 29. Copyright 1996, by AON.

In these cases, we are dealing with the psychological impact of aerial threats on aircraft crews. Therefore, it can be assumed that under heavy ground-based fire some of the pilots will perform their tasks in great haste or will abort the mission in fear of losing their own lives.

Following this line of reasoning, it can be concluded that in the case of determining the efficiency of air defense, it will not be only the resultant of the physical destruction of a certain number of the enemy's aerial threats. By adopting this philosophy, it can be assumed that the air defense will be effective when the fire of missiles and artillery will leave the enemy unable to destroy the troops (objects) covered by the air defense forces and, as a result, will not fulfil the combat task.

Therefore, the characteristics of the air defense were determined depending on the efficiency value expressed as a percentage (Table 1).

Table 1.
Characteristics of air defense depending on the value of its efficiency EOP

Air defense efficiency coefficient value	Characteristics of air defense	Expected results
30 % and more	Very strong	Destruction of the enemy air force on day 1 of air operation
20 - 29 %	Strong	Ceasing the air operation within 2-3 days
10-19 %	Average (sufficient)	Maintaining status quo in the air space
Below 10 %	Poor (insufficient)	Winning the control over the airspace by the aerial threats

Adopted from: "Obrona powietrzna" by B. Zdrodowski et al., p. 32. Copyright 1996, by AON.

On the basis of the conducted research, it was established that, in order to prevent the performance of tasks by the aerial threats, they should be contrasted with the air defense potential. It will be characterized by an efficiency index of 30% to 50%, depending on the share of unmanned aerial threats in the total number of aerial threats affecting the covered troops (facilities). Then, such an air defense can be considered very strong and sufficient, because it promises that on the first day of the operation (combat) the enemy's air operation will be ceased (the enemy's air force will be broken) and thus an absolute superiority in the air (air control) will be achieved. With the efficiency coefficient = 20-30%, conditions are created to break the enemy air operation within 2-3 days, and such an air defense should be described as strong. The efficiency around 10-20% ensures maintaining the status quo of the initial state in the aerial battlefield, i.e. the aerial threats will operate in a limited way, but neither side creates conditions for gaining an advantage in this dimension of the armed struggle. The air defense characterized by such a combat efficiency coefficient should be considered average (sufficient in the range of 10-19%). On the other hand, the efficiency below 10% is insufficient to effectively protect troops (facilities). Moreover, with such an air defense, there is a high probability that the aerial threats will achieve local or operational air control, which in turn may lead to a defeat in all aspects.

4. Determining the amount of aerial threats

The next step in determining the efficiency of air defense is the diagnosis of the capabilities of own forces and assets, expressed in the expected number of aircraft destroyed. In this case, the ability of these troops (including their individual components) to perform combat tasks resulting from the assumed intent, purpose and function of air defense. This ability in operational and tactical evaluation (calculations) is mapped using appropriate numerical indicators characterizing the space, time and effectiveness of air defense forces and its individual components (Halama, and Radomyski, 2003).

It follows that the anti-aircraft defense capabilities result primarily from the qualitative indicators of a particular combat asset and the number of missiles (ammunition) possessed by the given air defense system. In addition, the proposed solution was also extended with the environmental impact (terrain, weather) of the air defense systems. However, this time it was assumed that it may have a negative effect on the capabilities of the air defense. This is due to the fact that the capabilities of the air defense are calculated primarily on the basis of the tactical and technical data of the equipment, i.e. in ideal conditions. Therefore, it was assumed that along with the deterioration of environmental conditions, effectiveness will decrease of the air defense systems would degrade.

The general formula for the air defense capabilities therefore adopted the following form:

$$M_{AD} = \sum_{k=1}^{n} L_k * K_k * J_k - [(1 - W_E) * 100\%] \quad (5)$$

Where:

L_K – the amount of equipment of the k type air defense systems;

K_K – the k type AD system quality coefficient;

J_K – the number of missiles of the k type AD system;

W_E – environmental impact coefficient.

It follows that the capabilities of the air defense are directly proportional to the number of air defense equipment (sets, simultaneous engagement capability), their quality and the number of missiles and/or ammunition available

5. Determining the qualitative coefficients

The greatest challenge of the research was to determine the coefficients used in the algorithms presented. This was due to their qualitative nature and the confidential nature of some data (e.g. some tactical and technical data of aerial threats and air defense, and the probability coefficients of destroying the target of the missiles).

5.1. Aerial threats impact coefficient

Firstly, an assumption was made regarding the impact coefficient, which determines the percentage of the total combat potential that should be destroyed in order to achieve the goal of the operation. It was also specified that the goal of the action of the aerial threats may be:

Disruption - means that the operation of the object is disturbed, but still possible - 10% of the combat potential destroyed.

Disablement - means that the operation of the object is limited, and recovery to full operability is possible after repairing or replenishing losses - 30% of the combat potential destroyed.

Destruction - means that the object is out of service and cannot be repaired or refurbished - 60% of the combat potential destroyed.

5.2. Defended assets survivability

Generalizing the combat life of the elements of the formation on the battlefield, it was assumed that from a technical point of view (not taking into account the battlefield environment), the following factors will affect the combat life: the ability to recognize the object - i.e. its length and width, speed of movement and armor. The greatest importance is given to length (Wd) and width (Ws) and armor (Wo) - 0.3 each, and the march speed 0.1 (Wpm). From the obtained calculations for individual types of combat equipment, the average value adopted was 3.3, therefore this value was adopted as the unit of the quality coefficient of combat life. Ultimately, the calculation of the combat life took the following form:

Table 2.
Combat life coefficient of the selected military equipment

Coefficient multiplication index	Width [m]	Ws 0.3	Length [m]	Wd 0.3	March speed [km/h]	Wp 0.1	Armor	Wo 0.3	Wż 3.30
Leopard tank	2.7	0.81	3.7	1.11	70	7	2.5	0.75	**1.43**
PT-91 tank	3.5	1.05	9.6	2.88	60	6	2.5	0.75	**4.12**
Infantry Fighting Vehicle	2.3	0.69	5.7	1.71	100	10	1.5	0.45	**1.61**
Reconnaissance Fighting Vehicle	2.9	0.87	6.7	2.01	100	10	1.5	0.45	**2.38**
23 mm ZUR-23-2	1.8	0.54	4.5	1.35	50	5	1	0.3	**0.33**
Automated command and staff vehicle	2.3	0.69	5.7	1.71	100	10	1	0.3	**1.07**
Engineering reconnaissance transporter	2.9	0.87	6.7	2.01	100	10	1	0.3	**1.59**
Engineering vehicle	2.8	0.84	6.4	1.92	60	6	1.5	0.45	**1.32**
Armored vehicle-launched bridge BLG-67M	3.2	0.96	10.4	3.12	50	5	1.5	0.45	**2.04**

5.3. SAM missile combat effectiveness coefficient

It is a factor that generalizes the probability of hitting a target with a rocket. The need to use this coefficient results from the classified nature of these data. Therefore, it was assumed that the guided missile has a 90% probability of hitting the target, and the unguided missile 70%.

5.4. Quality of the aircraft

Another variable related to the calculation of the aerial threats quantity is the aerial threats quality factor (or in other words - the combat value of the aircraft). Since efficiency is closely related to tactics, i.e. with the methods of performing combat tasks in a specific type of aircraft. The combat efficiency of a fighter will be considered in relation to tasks in the scenarios typical for attack aircraft (bombers, fighter-bombers, assault aircraft) will be evaluated in terms of effectiveness in operations against ground or surface targets.

The adopted procedure for assessing the combat value of airplanes included the following elements:

- determining the model parameters of airplanes performing various tactical tasks defined as fighting ground/surface targets;
- determining the values of coefficients that define the degree of compliance of parameters with the standard;
- calculating the partial components for determining the combat value of aircraft;
- determining the overall combat value of the tested aircraft.

The following physical parameters were included in the criteria for evaluating the combat value of airplanes:

- Maximum range
- Radar cross section
- Radar range
- Maximum speed at cruising altitude
- Cruising speed
- Maximum ceiling
- Weapon load capacity

It should be emphasized that during the research, other parameters characterizing the aerial threats were also distinguished, such as:

- maximum speed at low altitude,
- maximum climb speed,
- minimum flight speed,
- number of simultaneously tracked targets,
- number of simultaneous engagement capability (missile),
- maneuverability and thrust vectoring ability,
- spatial parameters of the on-board air and ground target detection and destruction system,
- supercruise flight capability,
- advanced stealth systems,
- rescue, warning and survival systems,
- the scope of using external C4I systems,
- ability to steer unmanned platforms.

However, due to the degree of repetitiveness of the respondents' answers and in order to simplify the calculation, the scope was limited to the seven previously mentioned parameters.

The reference model, adopted to determine the basic combat value indicators and measurements of the analyzed potential enemy aircraft, was based on the Su-25 aircraft data. After calculating the comparative indicators for the detailed parameters of the aircraft, the partial indicators of the combat value were calculated. The obtained results are presented in Appendix 1.

5.5. Type *k* air defense system quality coefficient

For the purposes of the research, it was necessary to compare the combat potentials of anti-aircraft units and sub-units equipped with various anti-aircraft equipment. Therefore, in order to use formula 2, it was necessary to create two databases. The first was a database of anti-aircraft units and sub-units, containing data on the structure, equipment and quantities of anti-aircraft equipment. The second was the anti-aircraft equipment database, containing basic tactical and technical data of the equipment and the calculated quality coefficient of the given type of anti-aircraft equipment.

Determining the quality coefficients for the given type of combat equipment began with the selection of a list of factors characterizing the combat capabilities of anti-aircraft equipment.

From among these factors, those which significantly affect the combat potential of anti-aircraft units and sub-units were selected. They include:

- probability of hitting the target;
- slant range border of the SAM engagement envelope;
- altitude border of the SAM engagement envelope;
- multiple target engagement capability;
- firing cycle;

- time to be ready to open fire from the march position;
- marching speed on dirt roads;
- the ability to cross fords, bridges, ferries and ditches.

The remaining factors were rejected because they are secondary indicators or they have little or no impact on the final result of the study. Secondary indicators include the probability of hitting a target with n number of missiles, which are derivatives of the probability of hitting a target.

The next research step was to define the reference coefficient and the rules for calculating the coefficients for individual pieces of equipment.

The coefficient was calculated with the following formula:

$$JWJ_{AD} = \frac{W_i}{W_w} \qquad (6)$$

Where:

W_i - the conversion factor of the i-th type of anti-aircraft equipment

W_w - the conversion factor of the reference type of anti-aircraft equipment

As a model factor, or a reference factor, the factor calculated for a single OSA anti-aircraft combat vehicle (SA-8) anti-aircraft combat vehicle firing a series of two missiles (in the normal mode of fire). Therefore, for OSA anti-aircraft combat vehicle, the value of the JWJ qualitative index is one.

$$JWJ_{AD} = \frac{W_i}{W_w} = 1 \qquad (7)$$

The value of the conversion factor was calculated as follows:

$$C_K = C_P + C_{DG} + C_{GG} + C_{CS} + C_{TG} + C_{VM} + C_M \qquad (8)$$

Where:

C_P - coefficient taking into account the probability of hitting the target;

C_{DG} - coefficient taking into account the further border of the SAM engagement envelope;

C_{GG} - coefficient taking into account the upper border of the SAM engagement envelope;

C_{KC} - coefficient taking into account the number of simultaneous engagement capability;

C_{CS} - coefficient taking into account the firing cycle;

C_{TG} - coefficient taking into account the time to be ready to open fire from the march position;

C_{VM} - coefficient taking into account the marching speed on dirt roads;

C_M - coefficient taking into account the ability to cross fords, bridges, ferries and ditches.

From the defined dependencies, the Ck coefficient was calculated for a given type of set (measure) of air defense. The values of this coefficient for the selected sets are presented in Table 3.

Table 3.
Value of the Ck coefficient for the selected SAM system

Item	Name of equipment	Kk coefficient
1	AVANGER	1.77
2	BUK (SA-11 Gadfly)	10.59
3	CAROL	1.48
4	HAWK	5.80
5	KUB (SA-6 Gainful)	0.72
6	MANPADS	0.47
7	MISTRAL	0.25
8	S-125 NEWA (SA-3 Goa)	1.16
9	9K33 OSA-AK (SA-8 Gecko)	1.00
10	PATRIOT	2.59
11	RAPIER FSB2	0.72
12	RAPIER FSC	0.83
13	REDEYE	0.16
14	S-300W (SA-12A Gladiator)	3.92

5.6. Environmental impact coefficient

As part of the calculation function, it is calculated how the user-determined atmospheric (weather) and terrain conditions affect own and enemy troops. In order to determine the degree of impact, the program uses the sum of the individual components of the coefficient. This means that the impact of the environment (Wen) is the sum of the impact of weather conditions (Wwth) and terrain conditions (Wt).

$$Wen=Wwth+Wt \quad (9)$$

The weather impact indicator is the sum of the influence of wind, rainfall, fog, cloudiness and temperature, while the field impact indicator is the sum of the influence of the terrain in terms of observation, masking, obstacles, key terrain and approach and maneuver paths. The values assigned to particular parameters oscillate between 1-2% depending on the degree of their impact on the operation (1% - medium impact; 2% - high impact).

6. Conclusion

In conclusion, it should be stated that the air defense efficiency is a numerical value that determines the degree of adaptation of the air defense system to the implementation of the given task. This indicator can be used in both ex ante[1] and ex post[2] evaluations. It is also undoubtedly an important element, inseparable in the decision-making process and in the assessment of the possibility of completing the task by air defense units and sub-units.

The proposed methodology for determining the efficiency of air defense in the tactical level of command, along with algorithms and mathematical formulas, should be treated as the subject of further scientific considerations and at the same time constitutes a kind of invitation to a scientific discussion, which will allow for its improvement. We are also deeply convinced that despite the qualitative nature of the research and many limitations resulting from the extensive nature of the problem under consideration, our study generated the interest of the reader.

For the future study, we are planning to compare real life experiences with the method and equations proposed in this article.

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[1] Ex ante evaluation – a term for an analysis aimed at identifying (assessing) the need for a specific activity carried out before its implementation. Ex ante in Latin means in advance, before something happens.

[2] Ex post evaluation – assessment (evaluation) of the project or undertaking after its completion.

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Appendix

Basic tactical and technical parameters of aircraft used by the Air Force of the Russian Federation

	Range max [km]	Wz max	SOP [m2]	Wsop	Radar range [km]	Wzr	Max speed [km/h]	Wpmax	Cruising speed [km/h]	Wpprzel	Max ceiling [km]	Wpumax	Load [T]	Wumax	JWJ * 100
Coefficient multiplication index	0.1		0.1		0.1		0.1		0.3		0.1		0.3		
MIG-25	1865	186.5	4	0.025	100	10	3390	339	2500	750	23	2.3	5	1.5	1.2
MIG-29	1500	150	3	0.03333	70	7	2400	240	1500	450	18	1.8	5.5	1.65	0.32
MIG-31	3300	330	3	0.03333	160	16	2500	250	1500	450	24.4	2.44	6	1.8	2.55
MIG-35	2000	200	2	0.05	160	16	2560	256	1500	450	17.5	1.75	6.5	1.95	1.84
Su-24	940	94	3	0.03333	150	15	2320	232	1530	459	17.5	1.75	9	2.7	0.69
Su-25	500	50	3	0.03333	100	10	880	88	600	180	10	1	4.3	1.29	1
Su-27	3790	379	4	0.025	240	24	2450	245	1350	405	18	1.8	8	2.4	2.86
Su-30	3000	300	4	0.025	240	24	2600	260	1650	495	23	2.3	8	2.4	3.75
Su-34	4000	400	2	0.05	240	24	2200	220	1300	390	14	1.4	8	2.4	4.06
Su-35	3600	360	1	0.1	398	39.8	2750	275	1300	390	18.8	1.88	8	2.4	20.35