Research on the weapon target assignment problem in the combined air defense missile system for training simulation

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ABSTRACT

In modern warfare, when the weapon system and the targets are constantly being improved and upgraded, ensuring the distribution of firepower to optimally destroy the target will help the commander to make quick and accurate decisions, thereby improving combat effectiveness. This paper proposes a method to build a command-control automatic system based on solving the weapon target assignment (WTA) problem in a combination of short and medium-range air defense missile systems so that the total damage of targets is maximum and the damage of protected area is minimum. Based on combinatorial optimization algorithms, the probability of kill, linear programming method using Hungarian algorithm, the paper presents a mathematical model of WTA and its optimal solution for short- and medium-range air defense missile systems serving the training simulation problem, thereby giving the results of evaluating the effectiveness of the algorithm.

Keywords: WTA – Weapon Target Assignment; ACS – Automatic Control System; Training Simulation; PoK – Probability of Kill.

1. INTRODUCTION

WTA is one of the most important problems in controlling air defense missile systems. It has an important role cause in the process of air defense command; the speed of decision-making and the accuracy of decisions will greatly affect the effectiveness of using the air defense units. Normally, ACS solves problems in the following order: target detection, target identification, threat evaluation, and resource allocation. In this paper, we assume that the information about the attack of targets, the target's characteristic parameters (air situation picture - ASP) are known in advance; the problem is to build the WTA algorithm for air defense system with a variety of anti-aircraft missiles from short to the medium range so that the damage caused by the enemy is minimum and the ability to destroy the target is maximum. The complexity of the problem can be shown through the example in figure 1. It is assumed that the air defense unit has the task of destroying air targets by air firing units to protect the assets. To be able to make decisions, the headquarter (HQ) needs to know information about the state of the units, the assets, and ASP. This information is transferred to the headquarter by the radar stations, from the units, and the assets. In addition, information can also be received from external sources such as the nearest radar station, superior headquarter, adjacent headquarter. Thus, to make a correct decision, it is necessary to have a complete and accurate picture of the situation in the air and on the ground, which can only be obtained after processing all the information received in the headquarter. The situational parameters include the number of targets, target's motion parameters, type and threat level of targets, the number and location of the firing units, the time of each firing cycle, the characteristics of the combat capabilities of the units (ranges, flight altitude, one-shot PoK, etc.), coordinates of the protected assets, area and values of these objects. After receiving this information, the headquarter needs to evaluate the situational parameters and find the optimal plan to assign the targets to the firing units.

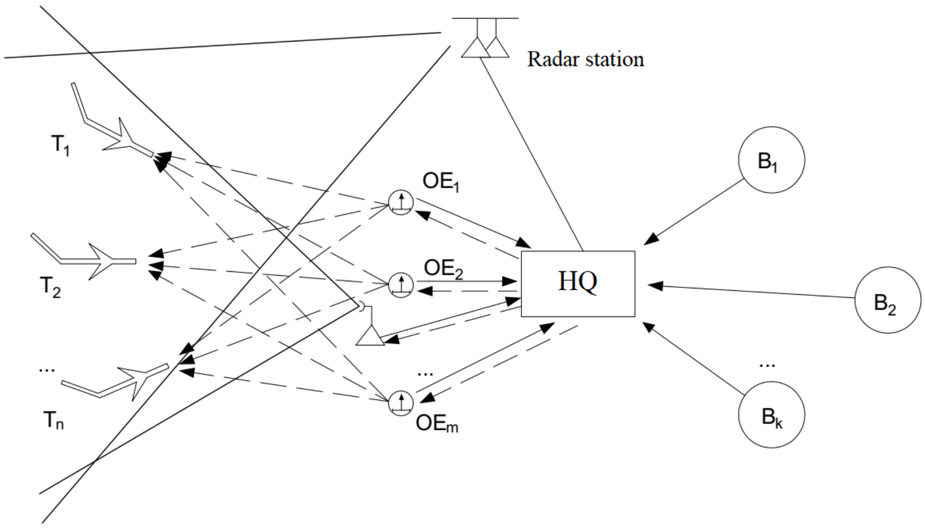

Figure 1. *WTA problem in ACS.*

2. MATHEMATICAL MODEL AND ALGORITHM OF WTA PROBLEM BASED ON LINEAR PROGRAMMING

2.1. Mathematical model of WTA problem

Let: W – The number of weapons; T – The number of targets; u_i – Integer value represents the priority of attack on target *i*, a larger value corresponding to higher priority, p_{ij} – PoK of target *i* in a single shot by weapon *j*; x_{ij} – A binary variable indicating whether weapon *j* engages target *i* or not. If $x_{ij}=1$ - Target *i* is assigned to missile *j*, otherwise $x_{ij}=0$. The mathematical model of the WTA problem is presented as follows:

Consider the objective function:

$$F=\sum_{i=1}^{T}u_i\left(\prod_{j=1}^{W}\left(p_{ij}\right)^{x_{ij}}\right) \tag{1}$$

Function F represents the total PoK, so if F reaches the maximum, we will have the highest attack efficiency. Assume that each weapon is assigned to a target and that no weapon is not assigned to a target; a weapon is assigned to only one target. Thus, we have the following condition:

$$\sum_{i=1}^{T}x_{ij}=1,\qquad j=1,2,\ldots,W \tag{2}$$

In the case of *W=T,* each weapon is assigned to only one target, let *W=T=N,* we have:

$$\sum_{i=1}^{N} x_{ij} = 1, \quad i = 1, 2, \ldots, N; \ \sum_{j=1}^{N} x_{ij} = 1, \quad i = 1, 2, \ldots, N \tag{3}$$

In summary, the mathematical model:

$$\max F = \sum_{i=1}^{T} u_i \left(\prod_{j=1}^{W} \left(p_{ij} \right)^{x_{ij}} \right) \tag{4}$$

where,

$$\sum_{i=1}^{N} x_{ij} = 1, \quad i = 1, 2, \ldots, N; \sum_{j=1}^{N} x_{ij} = 1, \quad i = 1, 2, \ldots, N; x_{ij} \in \{0,1\}^{N^2} \tag{5}$$

This is an optimization problem with a nonlinear model and a zero-one constraint; that is, the value of x can only have two values, 0 or 1. To give an algorithm to solve the above problem, this paper focuses on solving a specific task for an air-defense battalion equipped with specific weapons as follows:

+ The battalion has 6 missile firing units (MFU), in which 3 short-range (SR) MFU with up to 4 missiles on each, 3 medium-range (MR) MFU with up to 8 missiles on each.

+ Each MFU has 2 types of missiles; all of the missiles are fire-and-forget type and therefore can be considered as an independent channel.

+ Targets are divided into 3 groups with different technical-tactical missions, including: group 1 – fighter and gliding bomb; group 2 – cruise missile and smart weapon (SW); group 3 – UAV and helicopter.

Since the characteristics of the air defense problem are high speed, quick maneuvering targets, and their ability to change tactics flexibly, the calculation time must be fast enough to prevent the enemy's attack intentions. Thus, the WTA problem is essentially an optimization problem in terms of time and efficiency to maximally destroy targets, and the damage caused by the enemy is minimal. There are many methods to solve this optimization problem, such as using linear programming or using super simulation optimization algorithms [2], including *ant colony optimization algorithm (ACO), genetic algorithm (GA), particle swarm optimization (PSO)*. The limitation of these algorithms is the calculation time, so it does not satisfy the requirements of real-time. Linear programming is an optimization technique for a system of linear constraints and a linear objective function. An objective function defines the quantity to be optimized, and the goal of linear programming is to find the values of the variables that maximize or minimize the objective function. In linear programming, there are also different methods to solve the proposed optimization problem, such as the geometric method, the simplex method, and the Hungarian method [1, 3]. The advantage of the geometric method is a clear and easy calculation with a small number of targets and firing units. The limitation of this method is the high computation time if the size of the optimization matrix is large. In our problem, with the given input parameters, there will be a total of 36 channels corresponding to 36 rows of the matrix to be optimized. Therefore, using the geometric method will not satisfy the criterion of time. The simplex method is based on the mathematical model of the transport problem [1], it can solve the WTA problems without adding additional constraints related to the size of the optimization matrix and can be applied to all WTA problems based on minimization of the objective function. However, its limitation in calculation time still remains. Through experimental calculations with different calculation methods, in this paper, we choose a linear programming method that uses the Hungarian algorithm to solve the problem because this method gives the optimal solution in desired time even with a large optimization matrix.

2.2. The Hungarian algorithm

The Hungarian method is a combinatorial optimization algorithm that solves the assignment problem according to the criterion of the maximal objective function. For the WTA problem in air defense systems, if the objective function is based on the maximum damage of the enemy, the Hungarian algorithm is the most appropriate in terms of both time and effectiveness criteria.

Assume that the air defense battalion has some firing units with *k* channels, the number of targets is *l*. The mission is evaluated by the efficiency criterion expressed in the form of mathematical expectations of the number of destroyed targets, which is the result of assignments of all *k* missiles (channels) to all *l* targets. In this case, let *k=l*. The combat effectiveness of missile *i* against the *j* target is characterized by the corresponding element of the square matrix:

$$\left\| Q_{ij} \right\| = \left\| \begin{matrix} Q_{11} \ Q_{12} \ldots Q_{1l} \\ Q_{21} \ Q_{22} \ldots Q_{2l} \\ \ldots\ldots\ldots\ldots\ldots \\ Q_{k1} \ Q_{k2} \ldots Q_{kl} \end{matrix} \right\|; \ \left\| z_{ij} \right\| = \left\| \begin{matrix} z_{11} \ z_{12} \ldots z_{1l} \\ z_{21} \ z_{22} \ldots z_{2l} \\ \ldots\ldots\ldots\ldots\ldots \\ z_{k1} \ z_{k2} \ldots z_{kl} \end{matrix} \right\| \tag{6}$$

It is necessary to assign *k* missiles to *l* targets in the most optimal way, that is, find the elements of the solution matrix in (1.6) satisfying the limits (1.8). This will ensure the highest overall efficiency of using missiles. The mathematical model of this problem is written in the following form:

It is necessary to maximize the objective function:

$$L = \sum_{i=1}^{k} \sum_{j=1}^{l} Q_{ij} z_{ij} \tag{7}$$

subject to constraints:

$$\sum_{i=1}^{k} z_{ij} = 1; \ j = \overline{1,l}; \ \sum_{j=1}^{l} z_{ij} = 1; \ i = \overline{1,k}\,; \ z_{ij} = 0 \text{ or 1 with all } i,j \tag{8}$$

To optimize the solution by the Hungarian method, we use the principle of equivalence transformation of the efficient matrix, in which the optimality of the solution will not change when increasing or decreasing all the elements of the row (or column) by the same constant value.

The process of finding the optimal solution by this method can be divided into 3 stages: preparation stage, checking the optimality of the solution; find the optimal solution (computational loops). Details of these stages are presented in the flowchart in figure 2.

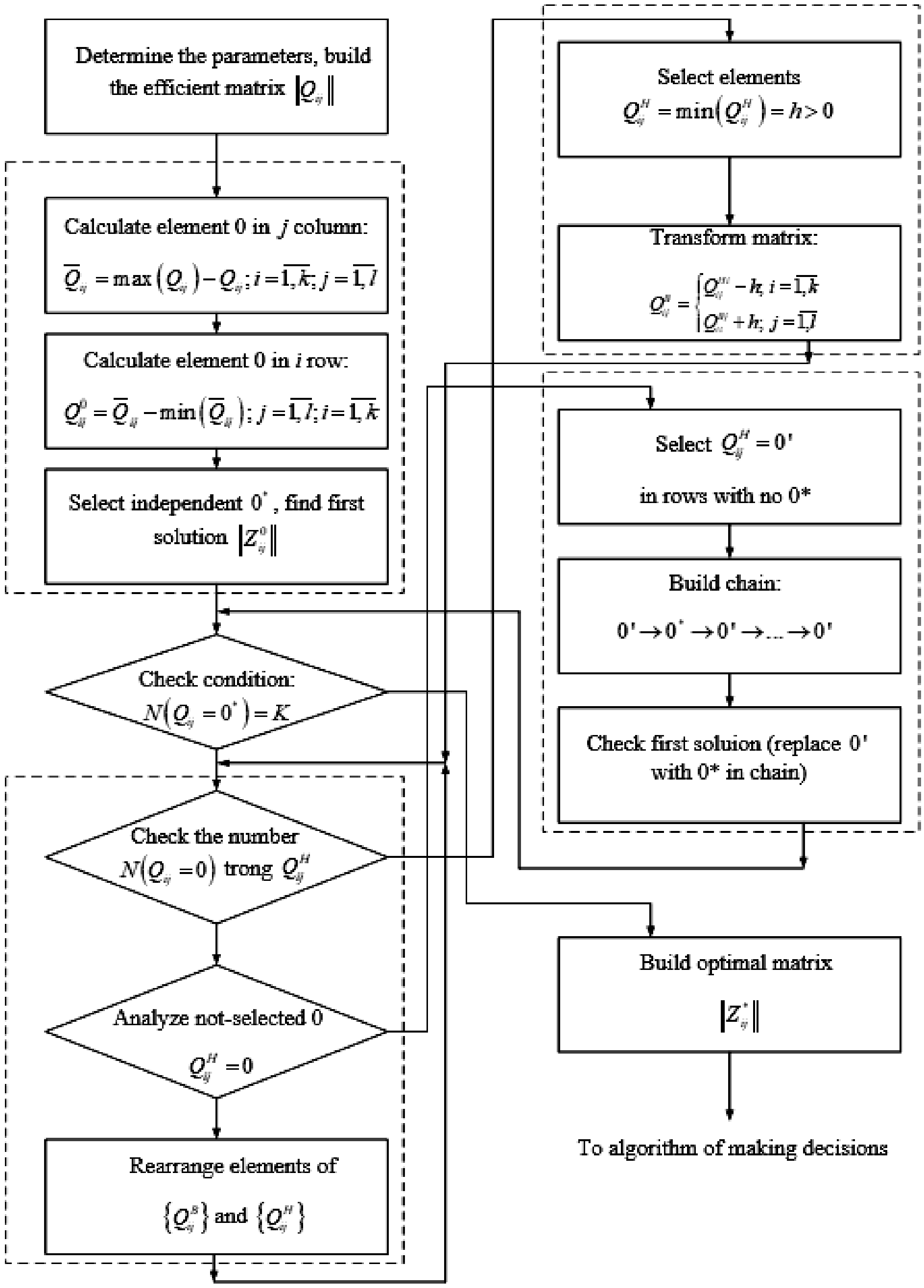

Figure 2. *Flowchart of the Hungarian method.*

To learn more about the Hungarian algorithm applied to WTA problems, we perform an example of finding the optimal solution in section 3 below.

3. SIMULATION AND DISCUSSION

To illustrate how to solve the WTA problem using the Hungarian algorithm, the authors first use a random efficient matrix of size 6x6, with a low-perfomance computer (Celeron G3930, 2.90 GHz, 2 M, 2 Gb RAM), Visual Studio 2013 programming tool, C# with .Net 4.5 libraries. The calculation steps are shown below:

Step 1 (*figure 3b*): Transforming matrix, ensuring that there is at least one zero element in each row and each column.

0.2	0.1	0.1	0.2	0.4	0.5
0.2	0.4	0.3	0.5	0.6	0.8
0.7	0.6	0.5	0.7	0.8	0.8
0.1	0.8	0.7	0.9	0	0.9
0.4	0.6	0.9	0	0.1	0.9
0.8	0.8	0.1	0.2	0.3	0

Figure 3a. *Initial matrix.*

0.2	0.3	0.4	0.3	0	0
0.5	0.3	0.5	0.3	0.1	0
0.1	0.2	0.4	0.2	0	0.1
0.7	0	0.2	0	0.8	0
0.4	0.2	0	0.9	0.7	0
0	0	0.8	0.7	0.5	0.9

Figure 3b. *Step 1.*

0.2	0.3	0.4	0.3	0*	0
0.5	0.3	0.5	0.3	0.1	0*
0.1	0.2	0.4	0.2	0	0.1
0.7	0*	0.2	0	0.8	0
0.4	0.2	0*	0.9	0.7	0
0*	0	0.8	0.7	0.5	0.9

Figure 3c. *Step 2.*

Step 2 (*figure 3c*): Select independent "0*", marked by red color. Check the number of "0*", there are 5 "0*". Continue the algorithm.

0.2	0.3	0.4	0.3	0*	0
0.5	0.3	0.5	0.3	0.1	0*
0.1	0.2	0.4	0.2	0	0.1
0.7	0*	0.2	0/	0.8	0
0.4	0.2	0*	0.9	0.7	0
0*	0	0.8	0.7	0.5	0.9

Figure 3d. *Step 3.*

0.2	0.3	0.4	0.3	0*	0
0.5	0.3	0.5	0.3	0.1	0*
0.1	0.2	0.4	0.2	0	0.1
0.7	0*	0.2	0/	0.8	0
0.4	0.2	0*	0.9	0.7	0
0*	0/	0.8	0.7	0.5	0.9

Figure 3e. *Step 4.*

0.1	0.2	0.4	0.2	0*	0
0.4	0.2	0.5	0.2	0.1	0*
0	0.1	0.4	0.1	0	0.1
0.7	0*	0.3	0/	0.9	0.1
0.3	0.1	0*	0.8	0.7	0
0*	0/	0.9	0.7	0.6	1

Figure 3f. *Step 5.*

Step 3 (*figure 3d*): Find element "0" in not-selected positions. It's the element [4,4]. Mark this "0/" element by yellow. Select the 4th row and deselect the 2nd column, which has independent "0*".

Step 4 (*figure 3e*): Repeat the process, we have element [6,2]. Select the 6th row and deselect the 1st column.

Step 5 (*figure 3f*): Find no "0" in not-selected elements. Turn to the next step to find the minimum of not-selected elements. The result is 0.1. Transform according to the 9th block in the flowchart and obtain the below matrix.

0.1	0.2	0.4	0.2	0*	0
0.4	0.2	0.5	0.2	0.1	0*
0/	0.1	0.4	0.1	0	0.1
0.7	0*	0.3	0/	0.9	0.1
0.3	0.1	0*	0.8	0.7	0
0*	0/	0.9	0.7	0.6	1

Figure 3g. *Step 6.*

0	0	0	0	1	0
0	0	0	0	0	1
1	0	0	0	0	0
0	0	0	1	0	0
0	0	1	0	0	0
0	1	0	0	0	0

Figure 3h. *Step 7.*

Step 6 (*figure 3g*): Continue to find element “0” in not-selected elements. The result is the element [3,1]. This is the only element “0” in row satisfying condition (6) in the flowchart.

Step 7 *(figure 3h):* Transform chains 3,1 → 6,1 → 6,2 → 4,2 → 4,4. Replace “0/” with “0*” and vice versa.

The number of "0*" is now 6, equal to the size of the matrix. Thus, the optimal condition is satisfied, end of testing. Replace the elements "0*" with the value "1". Entire elements of the matrix take the value "0". This is the solution. From the results in figure 3h, the assignments are as follows:

M1 is assigned to T5, M2 is assigned to T6, M3 is assigned to T1, M4 is assigned to T4, M5 is assigned to T3, M6 is assigned to T2.

To test the performance of the Hungarian algorithm, we simulate the WTA problem when the number of missiles is not equal to the number of targets. Specifically, the authors present simulation results for the case that the air defense system is fully equipped and has to attack 20 targets of various types and different distances. The MFUs are arranged 3-5km apart from each other. The parameters of PoK, TE, and distances to the MFU (in *km*) are described in *tables 1 and 2* below.

Table 1. *Target’s PoK and TE.*

	Fighter	Helicopter	UAV	Cruise Missile	PGM	SW
PoK	0.8	0.8	0.8	0.7	0.7	0.7
TE	0.9	0.5	0.5	0.7	0.9	0.7

The initial efficiency matrix is built based on PoK, TE, and distancing coefficients (the closer the target, the higher the coefficient). The range of short-range missiles is 20km, of medium-range is 50km. If the target is within the range of both short- and medium-range, then short-range is preferred (according to technical features of the system). Due to the modernity of the system, all missiles are capable of fire-and-forget mode, as well as the ability to maintain control of 20 missiles in the air at the same time, the missiles on each MFU can be considered as an independent channel. Thus, the initial effective matrix will have a size of 36x36, but since there are only 20 targets, it is necessary to add 16 columns (from column 21 to column 36) with all elements of 0 to ensure that the matrix is square. Then we can proceed to solve the problem as usual according to the algorithm.

The result is as follows:

- Short-range MFU: MFU1 is assigned to targets 8, 16, 17; MFU2 is assigned to targets 6, 13; MFU3 is assigned to targets 4, 12, 13, 15;

- Medium-range MFU: MFU4 is assigned to targets 1, 2, 5, 14, 18; MFU6 is assigned to targets 7, 9, 10, 11, 19, 20; MFU5 is not assigned to any targets.

- Through testing and evaluation on the real system in Battalion 61, with the initial parameters as in tables 1 and 2, the results obtained from the simulation completely coincide with the results in the real system.

Table 2. *Distances from targets to MFU.*

			Fighter					Helicopter				UAV			Cruise Missile			PGM			SW	
			T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20
SR	MFU1	M1	40	35	8	17	22	13	25	18	30	23	25	19	12	26	21	13	17	46	34	39
		M2	40	35	8	17	22	13	25	18	30	23	25	19	12	26	21	13	17	46	34	39
		M3	40	35	8	17	22	13	25	18	30	23	25	19	12	26	21	13	17	46	34	39
		M4	40	35	8	17	22	13	25	18	30	23	25	19	12	26	21	13	17	46	34	39
	MFU2	M5	43	34	6	13	23	12	24	19	28	21	22	17	9	29	18	15	19	47	31	36
		M6	43	34	6	13	23	12	24	19	28	21	22	17	9	29	18	15	19	47	31	36
		M7	43	34	6	13	23	12	24	19	28	21	22	17	9	29	18	15	19	47	31	36
		M8	43	34	6	13	23	12	24	19	28	21	22	17	9	29	18	15	19	47	31	36
	MFU3	M9	45	33	5	11	25	14	23	21	29	19	21	15	7	32	15	17	22	49	29	34
		M10	45	33	5	11	25	14	23	21	29	19	21	15	7	32	15	17	22	49	29	34
		M11	45	33	5	11	25	14	23	21	29	19	21	15	7	32	15	17	22	49	29	34
		M12	45	33	5	11	25	14	23	21	29	19	21	15	7	32	15	17	22	49	29	34
MR	MFU4	M13	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
		M14	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
		M15	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
		M16	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
		M17	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
		M18	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
		M19	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
		M20	47	38	11	15	18	16	28	15	27	18	27	21	13	25	19	12	19	43	32	41
	MFU5	M21	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
		M22	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
		M23	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
		M24	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
		M25	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
		M26	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
		M27	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
		M28	48	39	9	14	19	18	27	17	26	16	26	19	10	28	16	15	21	45	30	38
	MFU6	M29	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37
		M30	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37
		M31	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37
		M32	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37
		M33	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37
		M34	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37
		M35	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37
		M36	49	40	8	12	22	19	26	19	25	15	24	17	8	31	13	18	24	46	28	37

To evaluate the responding ability of the algorithm in time on the command computer, the authors conduct tests with different ASPs corresponding to the input matrices with different sizes. The test is taken with a data set of 1000 test samples corresponding to different ASPs including matrices with different sizes:10x10; 20x20; 50x50; 100x100; 250x250, the processing time on the computer are as follows:

Table 3. *Processing time with different ASPs.*

Size	10×10	20×20	50×50	100×100	250×250
Processing time, ms	0.003	0.020	0.320	2.616	41.630
Mean of optimization steps	4.90	11.19	14.79	23.85	43.93

From *table 3*, it can be seen that, as the matrix size increases, the number of optimal steps increases linearly with the number of input parameters. When the matrix size is 250x250, the processing time on the computer is 41.63 milliseconds. The ACS with the proposed algorithm above can satisfy the real-time response of modern air defense systems.

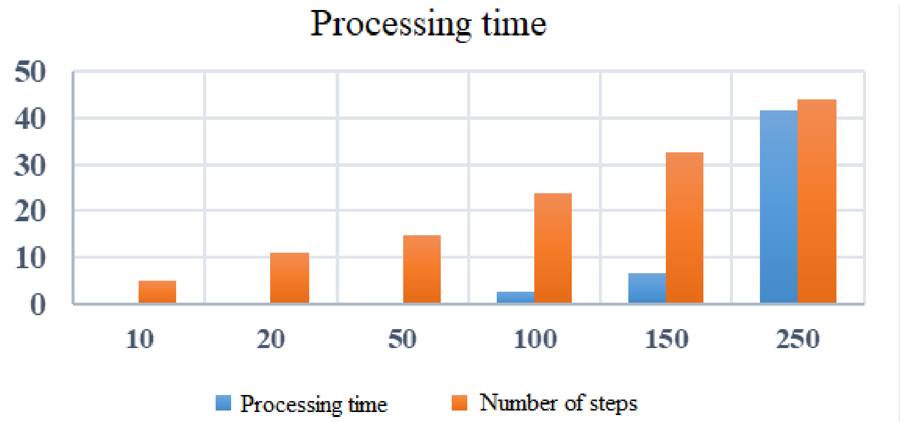

Figure 4. *Processing time and the number of steps corresponding to different matrix sizes.*

4. CONCLUSION

This paper presents the Hungarian algorithm to solve the WTA problem based on the linear programming method for an air defense battalion with actual parameters and information. The Hungarian algorithm is used to find the optimal solution of a linear programming problem when the ASP information, the parameters of each MFU, and the parameters targets are known in advance. Through researching and testing many WTA algorithms, the authors found that the Hungarian algorithm is the most suitable to solve the problem because it ensures the highest effectiveness, fast processing time, even for a low-performance computer, and satisfies the time requirements during combat conditions, suitable for modern air defense systems. Specifically, the algorithm can solve the WTA problem with a matrix size of 250x250 in only 41.63 milliseconds. Simultaneously, the simulation results through a real example with all MFU and 20 different targets also show the agreement with the results on the real system. This once again confirms the correctness of the algorithm in solving the WTA problem for training simulation.

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TÓM TẮT

NGHIÊN CỨU THUẬT TOÁN PHÂN CHIA HỎA LỰC TRONG TỔ HỢP TÊN LỬA PHÒNG KHÔNG PHỤC VỤ BÀI TOÁN MÔ PHỎNG HUẤN LUYỆN

Trong chiến tranh hiện đại, khi hệ thống vũ khí trang bị cũng như các mục tiêu tấn công đều không ngừng được cải tiến, nâng cấp, thì việc đảm bảo phân chia hỏa lực nhằm tiêu diệt mục tiêu tối ưu nhất sẽ giúp người chỉ huy ra quyết định nhanh chóng và chính xác, từ đó nâng cao hiệu quả chiến đấu. Bài báo đề xuất một phương án xây dựng hệ thống tự động hóa chỉ huy – điều khiển trên cơ sở giải bài toán phân chia hỏa lực trong tổ hợp hệ thống tên lửa phòng không tầm ngắn và trung sao cho hiệu suất tiêu diệt mục tiêu lớn nhất và giảm thiểu tối đa thiệt hại do hỏa lực địch tấn công khu vực được phòng thủ. Trên cơ sở các thuật toán tổ hợp tối ưu hóa, bài toán xác suất tiêu diệt mục tiêu, phương pháp quy hoạch tuyến tính sử dụng thuật toán Hungarian, bài báo đưa ra mô hình toán phân chia hỏa lực và giải bài toán tối ưu cho hệ thống tên lửa phòng không tầm ngắn và trung phục vụ bài toán mô phỏng huấn luyện, từ đó đưa ra các kết quả đánh giá hiệu quả của thuật toán.

Từ khóa: Phân chia hỏa lực - PCHL; Hệ thống tự động hóa chỉ huy/điều khiển – ASU; Đơn vị hỏa lực – ĐVHL; Tên lửa tầm ngắn – TLTN; Tên lửa tầm trung – TLTT; Sở chỉ huy – SCH; Tình huống trên không – THTK.

Correction Notice:

The article *"A mathematical model of flight control of anti-ship missiles"* (Section on Computer Science and Control Engineering, 2019, Special issue No.3, 2019, pp 71-77) was moved to the News and Views section.