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A Network Structure Optimization Method for Key Place Air Defense System

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Abstract: The key place air defense system is a complex giant system composed of various weapon systems. In this paper, the elements of air defense combat are decoupled and deployed, an optimization model aiming at the uniformity of the disposition direction, the uniformity of the coverage and the depth of interception of air defense fire, and the uniformity of the disposition direction, the uniformity of the coverage and the coverage area of the guidance radar are established, the network structure of the system is optimized by NSGA(Non-dominated sorting and sharing)-II, and the simulation results show that the method proposed in this paper can improve the combat capability of the system greatly.

Keywords: Key Place Air Defense; Operational deployment; Complex networks; Structure optimization

1.INTRODUCTION

Key place air defense system is a comprehensive integration of air defense combat weapon systems with various functions supporting each other and interacting with each other according to a specific deployment mode and architecture, the general term for a higher-level system that achieves the task of defending important regional or local targets. According to the basic viewpoint of system science, structure determines function. Under the condition of informationization, the operational capability of the system is determined not only by the capability of individual operational elements, but also by the whole network structure based on certain connection mechanism among operational elements.

Complex network theory is concerned with the interaction among the elements in a system. It studies various complex systems in society and nature by abstracting the relationships into topological structures and then by means of networks, surface-to-air missile is a holistic approach to modeling complex systems, Wang et al.(2017) based on the construction of a tactical level network model of the surface-to-air missile, which changes the network structure with a given probability of connection, the average path length and clustering coefficient before and after network optimization are obtained. He et al. (2016) constructed the network model of the air and space defense operational command architecture by the mapping method. On the basis of the traditional tree-like command level, different connection probability is adopted within and between the levels to increase the connection edge, the average degree of nodes, clustering Coefficient and average path length are analyzed. Zhang et al. (2015) constructed a complex network of combat system based on the Heterogeneity of nodes, taking the maximization of network profit and the minimization of network cost as the optimization goals, and proposed a control method to optimize the network connection of combat system. Li et al. (2018) constructed the evaluation index of network comprehensive operational capability based on function chain, the topology of the network is optimized by using the culture algorithm. Li et al. (2015) explored the inherent relationship between the command information system and the combat system, and constructed the hierarchical model of the combat system and the optimization model of the network structure. Li et al. (2016) put time into the research category of combat network, and put forward the contribution index of combat capability, which provides the train of thought for the optimization of system capability. Wang et al. (2016) analyzed the synchronization mechanism from the aspects of network topology and dynamic behavior of combat unit, and optimized the network structure by particle swarm optimization.

The above optimization methods are studied in the view of pure topology, the change of characteristic parameters of the complex network corresponding to the combat system is studied by changing the network connection relation, and the optimization of network structure is analyzed based on the characteristic parameters, this method neglects the heterogeneity of the nodes in the combat system network and their essential attributes. In the other part, the heterogeneity of the nodes is considered, and the self-defined index is used to evaluate the network, but the validity of the actual network structure has not been verified by simulation. In this paper, we propose to optimize the operational network structure based on the decoupling deployment of operational elements, which is verified by simulation experiments. The Operability is more directive to actual operations.

2.BASIC THERORY

2.1 Basic Knowledge of Air Defense Deployment

(a) Kill Zone

The kill zone of anti-aircraft missile weapon is a set of all points in the space where the probability of killing an air target

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flying in a constant speed horizontal straight line is greater than a certain critical value, generally taking the ground Cartesian coordinate system as the reference system, using the target's attack altitude to intercept the kill zone gives you a horizontal kill zone for a specific altitude target, as shown in figure 1.

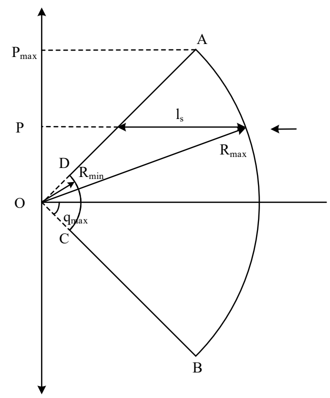


Fig.1. Schematic diagram of sector horizontal kill zone

AB —Kill Zone far boundary;
CD —Kill Zone near boundary;
MaxR—horizontal distance beyond the kill zone;
MinR —horizontal distance near the kill zone;
MaxP—maximum route shortcut;
l—Depth of horizontal kill zone with P Path shortcut.

(b) Mission Completion Line

In order to ensure the security of the protected object, it is necessary to destroy it at the farthest distance of the weapon launched by the air attack target platform. The loop formed by the farthest distance point is the enemy air attack completion mission line, as shown in figure 2.

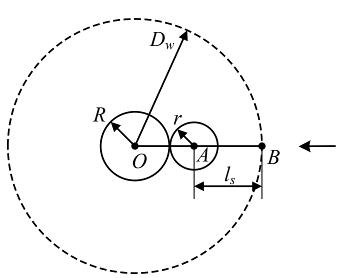


Fig.2. Mission completion line

In figure 2, D_w is the horizontal distance from the enemy's projectile line to the center of the defending target, representing the Mission Completion Line; R is the radius of the main ground; r is the effective kill radius of the enemy's ammunition warhead; and l_s is the effective range of the enemy's weapon, representing the distance between point A and B in figure, point A and point B represent the enemy weapon launch point and the explosion point respectively. When the attacking aircraft launches the missile at point B, the missile will detonate after its flight distance reaches point sl a, and the damage radius r reaches the edge of the important ground, the Circle corresponding to OB is the task completion line, and its formula is shown in formula (1).

$$D_w = R + r + l_s \tag{1}$$

2.2 Basic Knowledge of Complex Networks

In general, a graph is defined as $G = \{V, E\}$, where $V = \{v_1, v_2, v_3, v_4, \cdots, v_n\}$ represents the set of all vertices in the graph. The set of any combination of two points v_i and v_j in V is $[V]^2$, where $i, j = 1, 2, \cdots, n$, and $i \neq j$, then $E \in [V]^2$, represents the set of all edges in the graph. Similarly, in the theory of complex networks, the network can be represented as a graph of $G = \{V, E\}$ if the individuals in a network are abstracted as nodes and the relations between individuals are abstracted as edges. For any network G, if the edge v_{ij} between any two points i and j is the same edge, then G is called undirected network, otherwise G is called directed network. If the v_{ij} on either side of G has weight, then G is called weighted network, otherwise it is called unweighted network. Figure shows a directed weighted network. At the same time, the network nodes may not belong to the same class, then the network is called heterogeneous network, otherwise known as the quality network.

2.3 Principle of NSGAII algorithm

NSGA II (Corne,2000), which is a non-dominated sorting genetic algorithm with elite strategy, is one of the classical multi-objective genetic algorithms, the convergence of solution set is good and so on, so it is widely used. By simulating natural selection and genetic phenomena such as replication, crossover, and mutation, starting from a randomly generated chromosome population, and following the principles of selection, crossover, and mutation in genetics, a group of chromosome population with better fitness is generated. After multi-generation evolution, the whole population is developed to a better region in the search space. Finally, a population with better fitness is obtained, which is the optimal solution set of the problem. NSGAII algorithm replaces fitness function of genetic algorithm with elite selection strategy through multi-non-dominated sorting and crowding calculation.

3. DECOUPLING DEPLOYMENT OF COMBAT ELEMENTS

The traditional disposition of Air Defense Forces takes the fire unit as the minimum unit, and the operational factors are highly coupled, which greatly limits the defense range of air defense fire, the entire operational loop is caught in the risk of broken network broken chain. The fire unit is decoupled, the detection node, the command and control node and the strike node are distributed, the command and control node is networked, the launch unit is networked on demand, and can be connected to any effectively guided radar in the network, for a wider range of firepower.

After decoupling the combat elements of air defense firepower, the first thing to do is to optimize the deployment of the combat elements. When the direction of the target is known, the sector deployment is adopted to deploy in the key direction. Because the range of deployed position is a continuous space, it can be deployed in theory as long as the condition of deployment is satisfied. In this paper, a fixed-size grid is used to discretize the area to be deployed. The vertices of the grid represent deployable points, and their rectangular coordinates are expressed as *P (x, y)* and polar coordinates are expressed as *P (ρ, θ)*, as shown in figure 4, each intersection point *P (ρ, θ)* in the grid represents the position to be sampled, ρ represents the distance from the center of the position to be deployed, and θ represents the Azimuth of the position to be deployed relative to the center of the position to be deployed. At the same time, according to the actual terrain, if the intersection met the deployment conditions, then the point will be put into the alternate space, otherwise not put.

Traditional air defense forces are deployed with fire unit as the smallest unit and combat elements have high coupling degree, which greatly limits the defense range of air defense firepower. At the same time, due to the over-concentration of nodes of air defense operation chain, if any node is damaged, the whole operation loop will fall into the risk of network breaking and chain breaking. Decoupling the fire unit, distributed deployment of detection node, charging node and strike node, networking of charging node, launching unit as needed into the network, can be connected with any effective guidance radar in the network, to achieve a wider range of fire coverage.After the air defense firepower elements are decoupled, the operational elements need to be optimized first.In the case of the known direction of the target attack, the fan-shaped deployment mode is adopted to deploy the key direction. As the range of the deployment position is generally a continuous space, in theory, as long as the deployment conditions can be met, the position can be deployed. However, due to computing needs, the deployment scope is generally discretized first. In this paper, fixed-size squares are used to discretize the regions to be deployed. The vertex of the square represents deployable points, and its cartesian coordinates are *P (x, y)* and polar coordinates are *P (ρ, θ)*. As shown in FIG. 3, each intersection point *P (ρ, θ)* in the grid represents the points to be sampled in the deployment positions, and ρ represents the distance between the positions to be deployed and the important center. θ indicates the azimuth of the position to be deployed relative to the center of the important location. At the same time, according to the actual terrain, if the intersection meets the deployment conditions, the point will be put into the alternative space, otherwise not.

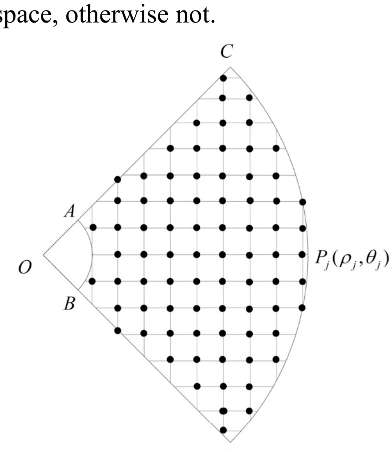


Fig. 3. Discrete map of deployment area

3.1 Optimal deployment model of air defense firepower

According to the basic principles of air defense fire deployment, this paper mainly considers the direction uniformity of fire deployment, the depth of fire interception and the fire coverage uniformity.

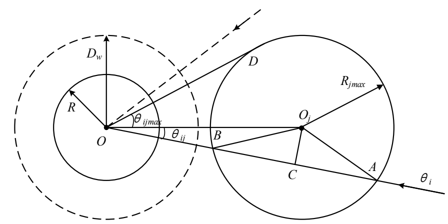


Fig. 4. Target track diagram

As shown in figure4, O for reclaiming center, $O_j(\rho_j,\theta_j)$ unit j deployment for launch point, O_jA is the far limit of the kill zone of launch unit J, and its size is $R_{j\max}$. $\alpha_i = (\cos\theta^i, \sin\theta^i) = (x_i, y_i)$ is the direction vector of the target incoming direction θ^i ; θ_{ij} is the included Angle between the approaching direction of the target θ^i and the polar direction of the deployment point of the launch unit θ_j, that is, the included Angle between the example OO_j and OA. $\theta_{ij\max}$ is the maximum route Angle between the incoming direction of the target and the launching unit, that is, the included Angle between OO_j and OD.

(a) Uniformity of fire direction (DU)

In this paper, it is assumed that all the incoming directions are centered on the important places, and the enemy target may attack in directions between θ_1 and θ_2. The possible Angle of attack direction from start to end is divided into *n* equal parts: θ^1, $\theta^2, \cdots,$ θ^n, $d\theta_j^i$ means that the target passes through the kill zone of a certain launching unit *j* in the direction of θ^i. Considering that the incoming target will pose a threat to our protected object once it enters the mission completion line, the $d\theta_j^i$ of this paper only takes the track between the incoming target entering the kill zone of the launching unit and the mission completion line. It represents the ability of firepower to intercept enemy aircraft outside the mission line. $d\theta^i$ represents the sum of the trajectories of all the transmitting units that the target may pass in the direction of θ^i, and its calculation is shown in Equation (2). $p\theta^i$ represents the ratio of the trajectories in the direction of θ^i to the sum in all directions, and the objective function is obtained in Equation (3).

$$d\theta_j^i = \begin{cases} 0, & O_jC \ge R_{j\max} \\ 0, & O_jC < R_{j\max},\ \rho_j < R_{j\max},\ OA \le D_w \\ OA - D_w, & O_jC < R_{j\max},\ \rho_j < R_{j\max},\ OA > D_w \\ 0, & O_jC < R_{j\max} \le \rho_j,\ \ OA \le D_w \\ 2AC, & O_jC < R_{j\max} \le \rho_j,\ OB \ge D_w \\ OA - D_w, & O_jC < R_{j\max} \le \rho_j,\ OB < D_w < OA \end{cases} \tag{2}$$

$$f_1 = -\sum_{i=1}^{n} p\theta^i \cdot log(p\theta^i) \tag{3}$$

(b) Depth of interception (ID)

Fire interception depth is defined as the target's flight path from entering the fire kill zone to leaving the kill zone (Chen, 2007). At the same time, the deeper the depth of fire interception is, the more chance of intercepting the target, the less the threat of the target to the important place. In direction θ^i, the intercept depth of a fire unit to a target is defined as the difference between the longest kill distance and the nearest kill distance of a fire kill zone to a target in that direction, since the killing zone within the task line of the attacking target can not stop the target from attacking the defending object, the intercept depth of this part is not calculated, therefore, the intercept depth of a single fire unit in I direction l_j^i is also calculated by Equation (2). The objective function is shown in Equation (4).

$$f_2 = \sum_{i=1}^{n}\sum_{j=1}^{m} l_j^i \tag{4}$$

(c) Uniformity of fire coverage (CU)

Given the amount of anti-aircraft fire and the area of responsibility, in order to avoid deployment, some areas overlap too much fire coverage, the other part of low overlap. The objective function is shown in Equation (5):

$$f_3 = \frac{\sum_{i=1}^{n}(m_i - \bar{K})^2}{n} \tag{5}$$

where, n represents the number of deployment points, m_i represents the number of each deployment point covered by firepower, and $\bar{K}$ represents the average number of each deployment point covered by firepower.

3.2 Optimal Deployment Model of guidance radar

The guidance radar is the eye of the surface-to-air missile, and the greater its coverage, the more time it takes to detect and track a target, and the more time it takes to launch a missile, the range of tracking and guidance is closely related to the height, velocity and radar cross-section of the attacking target. Antiaircraft fire can damage the target effectively only in the guidance range of the guidance radar. In this paper, the uncoupling deployment of guidance radar and launch unit is used to study the independent and decentralized deployment of guidance radar and launch unit. At the same time, based on the actual combat, command and control system and guidance radar together constitute a fire-control system, deployed in the same area, so in this paper the Fire Unit Command Vehicle and guidance radar deployed at the same point, do not do another study.

The guidance radar is deployed at the same discrete points as the antiaircraft fire. When the deployment position has been discretized and the detection radius and quantity of the guidance radar are known, a limited number of points are selected among the candidate deployment points to deploy the guidance radar, and at the same time, the uniformity of the radar coverage in all directions is maximized, the uniformity of the overall coverage is maximized, and the corresponding objective function is the same as the deployment model for antiaircraft fire, which is not repeated here. The difference is that due to the small number of guidance radars and the need to achieve the maximum coverage of the responsibility, an additional coverage area to maximize the optimal target, the optimal deployment model is as follows:

$$f = \bigcup_{i=1}^{n} S_i \tag{6}$$

Where S_i represents the coverage area of a single radar.

The optimization model of the deployment of combat elements is based on the discrete processing of the deployment area, and the variable space is large, so it is difficult to find the optimal solution by using the traditional optimization algorithm, therefore, the intelligent optimization algorithm is more appropriate for the solution, this paper chooses NSGAII Algorithm for the solution.

4. OPTIMIZED GENERATION OF OPERATIONAL NETWORK

According to the operational cycle theory, the basic process of air defense operations can be summarized as follows: after the upper detection entity finds the target, it sends the target information to the charging entity, and the charging entity makes up its mind after analyzing and judging, the attacking entity under its command intercepts the target with the cooperation of the guidance entity, thus completing the whole operation cycle. Based on the combat process, the nodes in the air defense system are abstracted as detection nodes, command and control nodes and strike nodes, and the target nodes are regarded as the antagonists of the system, not as the nodes in the system.

In the key place air defense system, the combat entities cooperate to accomplish the combat task through the interaction of information, which can be all kinds of visible and invisible energy or signal. For example, after the detection system finds the target through the radar electromagnetic wave, infrared and so on, the target information is sent to the command and control system through the wired or wireless transmission, command and control system through wired or wireless way to the Missile Launch Unit Command, Launch Unit Missile Kill and destroy the target. It can be seen that there are different kinds of mutual information in the whole combat link. In this paper, these mutual relations are abstracted into different links, which are detection chain, intelligence chain, accusation chain and strike chain.

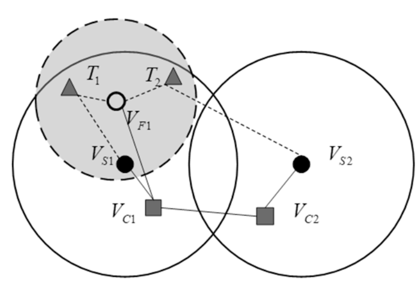


Fig.5. Sketch map of network edge model

As shown in Fig.5, V_S、V_C、V_F respectively represent detection node, command node and firepower node. $T_1 \to V_{S1}$ is detection chain, $V_{S1} \to V_{C1}$ is command chain, $V_{C1} \to V_{F1}$ is accusation chain, $V_{C1} \to V_{C2}$ is coordination chain, and $V_{F1} \to T_1$ is strike chain.

In the key place air defense system, the function chain is a continuous inertial chain path which is composed of the detection node, the command node and the strike node, as well as the intelligence chain and the command chain, is a series of air defense operation flow produced by the ability to strike air attack targets, the number of which can be used to characterize the operational capability of the system. Function chain can be divided into basic function chain and generalized function chain according to the number of nodes.In Figure 5, V_{F1} is within the effective coverage range of V_{S1}, $V_{S1} \to V_{C1} \to V_{F1}$ is an effective functional chain, while $V_{S2} \to V_{C2} \to V_{C1} \to V_{F1}$ is a connected functional chain, but V_{F1} is not within the guidance coverage range of V_{S2}, and is actually an invalid functional chain.Therefore, the number of effective functional chains is proposed as the evaluation index of system robustness.

The particularity of air defense operation lies in that the air defense missile can only finish attacking the target under the guidance of the Fire Control System composed of guidance radar and command and control vehicle, the relative position of Air Defense Fire and guidance radar determines the final effectiveness of fire, which is reflected in the operational network, that is, whether there is an effective connection between nodes.

Table 1 shows the pseudo-code of the operational network generation algorithm based on the deployment results and operational rules of air defense elements.

Table 1. Operational network generation algorithm

```
Combat_network_generate Algorithm
input Sensor, C2, Fire, Rs, Rf;
begin
  initialize the Sensor connecting to C2;
  for i in Sensor  connecting with C2
     for j in Fire
        d_ij = distance between i and j;
        if d_ij is the minimum then
           connect j to C2;
     end
   end
   for i in Fire connecting with C2
      for j in Sensor connecting with C2'
         if d_ij < Rs + Rf  then
            connect C2' to C2;
      end
   end
   return network;
end
```

After the operational network structure is determined, according to the network connection rules, each probe node points to a command node and is deployed in the same place, the command nodes cooperate with each other, and each fire node is commanded by only one command node.

The pseudo-code of the effective search algorithm for function chain is shown in Table 2.

Table 2 Effective function chain search algorithm

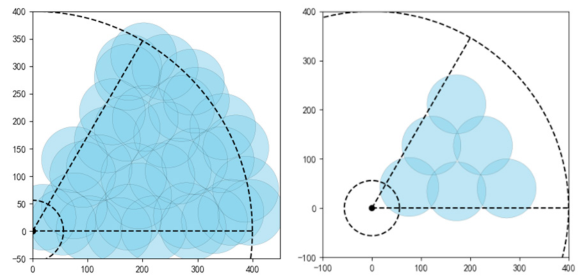
```
Function_chain_search Algorithm
input network, Sensor, C2, Fire, Rs, Rf;
begin
  initialize function_chain_list
  for i in Sensor  connecting with C2
     for j in Fire connecting with C2
        d_ij = distance between i and j;
        if d_ij < Rs + Rf  then
           put i→ C2→j into list;
     end
     for z in Fire connecting with C2'
        d_iz = distance between i and z;
        if d_iz < Rs + Rf  then
           put i→ C2→C2'→j into list;
     end
   end
   return function_chain_list;
end
```

5. CASE SOLUTION

In order to verify the method of network structure optimization of air defense system in key areas, the air defense scenario of red-blue confrontation is constructed, in which the red side is the defensive side and the blue side is the offensive side. The Red Square system consists of a tactical search-and-command radar and six anti-aircraft missile battalions, each comprising a command vehicle, a guidance radar and six launch vehicles, each equipped with four missiles, the horizontal kill radius is 60 km and the kill probability of a single missile is 0.8. The precision tracking range of the guidance radar is 100 km and the Azimuth is omnidirectional. The radius of the defensive stronghold is 20 km, the red side is deployed in an area with the center of the stronghold as the center, the radius is 400 km, and the direction is 0 ~ 60 °. The blue side is a target group composed of 40 aircraft, attacking the red side with 20 aircraft/minute evenly distributed in the defensive direction. The range of the airborne air-to-surface missile is 50 km and the effective damage radius is 1 km. In order to compare the effectiveness of this method, the network structure under element-coupled deployment with that under decoupling is tested and analyzed.

5.1 Combat deployment comparison

After the decoupling of the operational elements, the launching unit of the Launch Battalion and the guidance radar are no longer confined to the same location, and the wide-area distribution is realized. By solving the optimal deployment model, the optimal deployment schemes of Launch Unit and guidance radar are obtained, and the deployment schemes of all elements of air defense operation are combined. By solving, the deployment schemes of 4 launching units and 51 guidance radars are obtained respectively, and 204 overall deployment schemes are obtained by combining them, as shown in figure 6(a), the results of optimized deployment of the Launch Unit. Figure6(b) shows the deployment in factor coupling.



(a) Fire deployment diagram in decoupling
(b) Fire deployment diagram in coupling

Fig.6. Fire deploymen comparasion

When deploying the defense area of responsibility, the depth of interception and the uniformity of coverage under decoupling condition are much better than those under coupling condition. The main reason is that there are only 6 fire deployment points in the system when the combat elements are coupled, it can not cover the whole range of the responsibility defense, and the Directional uniformity index is not very different, because it only indicates whether the target track in each direction is uniform, but not the whole capability value. By comprehensive comparison, the deployment under the decoupled combat elements breaks the constraints of the fire unit itself and can achieve the maximum fire coverage, as shown in table 3.

Table 3 Comparison of results from different deployment scenarios

Factor decoupling			Factor coupling		
DU	ID	CU	DU	ID	CU
1.7918	9268	0.3787	1.7707	5174	0.1361
1.7635	9268	0.3764	1.7854	5156	0.1054
1.7915	9268	0.3786	1.7918	5059	0.0664

5.2 Network structure comparison

The operational network structure under each deployment scheme is obtained by the operational network generation Algorithm, and the effective functional chain number under each network is obtained by the effective functional chain search algorithm. The results show that the number of functional chains is 214 under decoupling condition, while the number of functional chains is only 36 under coupling condition.

5.3 Combat effectiveness comparison

In this paper, the target interception rate is selected as the evaluation index of system operational effectiveness, and 500 Monte Carlo Simulations are carried out on the combat system under the condition of decoupling and coupling of operational elements, the analysis of the simulation results shows that the interception rate of the air defense system to the attacking target is 99.055% under the decoupling condition, and the interception rate of the air defense system to the target is 94.76% under the coupling condition, under the condition of the same threat target, the operational capability of the system can be greatly improved by using the network structure under the condition of decoupling factors.

6.CONCLUSION

The air defense system of key areas is an important part of the air defense system of national territory, which undertakes the defense task of strategic important areas and important targets. In this paper, the elements of air defense combat are decoupled and deployed, and then the network structure of the system is optimized. The effectiveness of this method is verified by comparing the deployment and network structure optimization under the coupling of elements, the weapon system of the air defense system in the main area studied in this paper belongs to the same type. The next step is to study the mixed deployment and adaptive connection of different weapon system.

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