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Weapon system portfolio selection based on structural robustness

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Abstract: The system portfolio selection is a fundamental frontier issue in the development planning and demonstration of weapon equipment. The scientific and reasonable development of the weapon system portfolio is of great significance for optimizing the design of equipment architecture, realizing effective resource allocation, and increasing the campaign effectiveness of integrated joint operations. From the perspective of system-of-systems, this paper proposes a unified framework called structure-oriented weapon system portfolio selection (SWSPS) to solve the weapon system portfolio selection problem based on structural invulnerability. First, the types of equipment and the relationship between the equipment are sorted out based on the operation loop theory, and a heterogeneous combat network model of the weapon equipment system is established by abstracting the equipment and their relationships into different types of nodes and edges respectively. Then, based on the combat network model, the operation loop comprehensive evaluation index (OLCEI) is introduced to quantitatively describe the structural robustness of the combat network. Next, a weapon system combination selection model is established with the goal of maximizing the operation loop comprehensive evaluation index within the constraints of capability requirements and budget limitations. Finally, our proposed SWSPS is demonstrated through a case study of an armored infantry battalion. The results show that our proposed SWSPS can achieve excellent performance in solving the weapon system portfolio selection problem, which yields many meaningful insights and guidance to the future equipment development planning.

Keywords: heterogeneous combat network, structural robustness, weapon system portfolio selection, equipment development planning.

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1. Introduction

As a new engaging concept, network-centric warfare (NCW) is one of the main operational styles in the future information war, and its core is the counterwork which human controls between the equipment system and series centralized by the network. Joint operations and system confrontation under NCW are the fundamental demand for the development of future weapons and equipment, while the traditional platform-centered "chimney-style" development pattern and the fragmented decision-making process have greatly hindered the process of "joint capability integration" of scattered weapons and equipment at the system level. The pursuit of integration, generalization, and serialization of equipment development has become the distinctive features of the equipment informationization construction of our army. In the context of weapon system-of-systems (WSoS) construction, weapons and equipment development decisions are no longer limited to the selection of a single high-precision equipment from multiple alternatives, but more attention is given to cross-domain system portfolio evaluation and selection decisions. Facing an increasingly complex and uncertain battle circumstances, equipment development decision-making is becoming more and more difficult. On the one hand, it is impossible to develop a large number of repeated equipment at will under the constraints of limited budget; on the other hand, it is necessary to select the appropriate equipment system for development by capability requirements to adapt the complex environment of modern warfare. The structural robustness of the weapon equipment system is one of the important indicators that describe the overall capabilities of the equipment intuitively from the system level. In the rapidly changing complex battlefield environment, developing the potential weapon systems based on the structural robustness can help to optimize the weaponry and equipment architecture and improve the indestructibility of the equipment architecture, which is of great military value for seizing the initiative on the battlefield and achieving victory in the war. From the perspective of system-of-sys-

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tems level, research on the portfolio selection of weapons and equipment systems based on structural invulnerability is becoming an important research topic.

It is worth noting that weapon system portfolio selection problem is one of the important scientific issues of WSoS demonstration. The WSoS demonstration is a very complicated system engineering and involves many aspects of scientific issues, including military requirement demonstration analysis, WSoS architecture designment, operational capability evaluation, operational effectiveness simulation evaluation, weapon system portfolio selection, weapon contribution rate analysis, and so on [1, 2]. There also exists huge difference across different combat domains, such as air attack WSoS, air defense and antimissile WSoS, ground armored WSoS, and aircraft carrier WSoS. The modeling of the equipment system and the calculation of the structural invulnerability must consider the heterogeneity of the combat network, and the combination optimization should be considered reasonable. It is really hard to find a generalized framework to model and characterize the WSoS demonstration problem. Therefore, this paper only focuses on the system portfolio selection problem, which is an important scientific issue in WSoS demonstration, and takes an armored infantry battalion as an example to carry out research.

2. Related work

Weapons and equipment are characterized by complexity, intelligence, integration, and diversified capabilities [3−6]. Moreover, they transmit information through a variety of materials, energy, and information streams to cooperate with each other to complete combat missions. Therefore, modeling complex weapon systems is a challenging task [7]. Traditional system modeling frameworks mostly use tree-like network structures [8−10] to model and describe the system. However, it does not fully consider the impact of the mutual coupling and correlation between various equipment on the network's survivability. This lacks actual effectiveness, and it is impossible to evalute the effectiveness of every element in the weapon system. Rapid developments and advances of network science have allowed complex networks to become a powerful tool for characterizing the complexity of military organizations. The basic principle of a complex network is that it can abstract a large number of constituent elements in the system into nodes in the network, abstract the relationship between each element as an edge in the network, and convert system problems into network problems [11−13]. Tan et al. [14] studied the general steps of complex networks in the field of weaponry and equipment, and proposed a method for analyzing the network structure of the comprehensive evaluation index of the operation loop, which provided new ideas for the design and optimization of the architecture. Zhang et al. [15] proposed a modeling method of weapon equipment system based on the observation-orientation-decision-action (OODA) loop with the idea of network modeling. The above methods have fully considered the correlation between the equipment and the heterogeneity of the combat network.

The structural robustness research methods are mainly based on two categories: graph theory and statistical physics [16−23]. The former focuses on network topology analysis, and mainly analyzes the indestructibility of the network through some indestructibility indicators, such as dispersion, adhesion, integrity, toughness, connectivity, and hierarchical flow median [24]. Although the calculation results are accurate, they are not applicable to combat networks. First, the combat network is large in scale and the index is difficult to solve. The solution process is NP-hard. Second, the combat network is a heterogeneous network. Most of these methods focus on homogeneous networks. The latter focuses on the statistical characteristics of the network, which can solve the problem of the network scale and the focus is on the integrity of the network [25,26]. Its main indicators include natural connectivity, network efficiency, classification, and subnet clustering coefficient. Based on this, Li et al. [18] proposed a directed natural connectivity index as a measure of the survivability of combat networks; He et al. [27] used the network efficiency proposed by Latora to measure the survivability of equipment networks; Wang et al. [28] studied the structural robustness based on a super-network model, and summarized the survivability measurement indicators such as the natural connectivity of the network, the classification, the classification distribution, and the subnet clustering coefficient. However, most of the above methods also focus on homogeneous networks.

In the defense and military field, the earliest application of “portfolio selection” comes from Buede and Bresnick, and they applied the portfolio selection theory to the investment decision of the US Navy’s equipment projects [29]. Since then, most of the portfolio planning researchers who focus on the military field have focused their research on weapon system research and development or investment project portfolios [30−34]. Zhang et al. [35] utilized VIKOR technology to sort and screen weapon systems for a collective comparison matrix composed of experts representing different weights using fuzzy preference relationships to judge the standards. Li et al. [36] established a combat network-based project portfolio selection model with the optimization goal of maximizing weapon combination combat capabilities and constraints on capability requirements and cost. Zhou et al. [37] used fuzzy cluster analysis and maximum deviation method to obtain a weapon system combination by ranking all candidate equipment and calculating the weight of each weapon system in the composition. However, none of the above weapon system portfolio selection methods take into account the structural robustness of the equipment system. From the perspective of the system, this paper fully considers the correlation between different weapons and equipment, establishes a combat network model of the weapon and equipment system, and proposes a portfolio of weapons and equipment systems based on structural indestructibility to provide new ideas for the choice of weapon system portfolios. The contributions of this article are summarized as follows:

(i) A two-layer heterogeneous combat network model based on the operation loop theory to describe the weapon equipment system-of-systems scientifically and reasonably. The model fully considers the characteristics of the heterogeneity of the weapon equipment system, sorts out the different types of association relationships between the equipment in the system, and the relationship between equipment attributes.

(ii) A portfolio selection model of weapon equipment system based on structural invulnerability is proposed. This model fully considers the future capability requirements of the equipment system and the current budget constraints. The comprehensive evaluation index of the operation loop is introduced to quantitatively evaluate the structural invulnerability of heterogeneous networks, which reduces the difficulty of large-scale combat network computing.

(iii) Demonstrate and analyze the calculation process and results of weapon system combination selection based on structural invulnerability through an example, and compare the proposed method with traditional complex network indicators to further verify the effectiveness of the proposed method.

The structure of this article is as follows. Section 3 describes and analyzes the choice of weapon system portfolios. Section 4 models the combat network of the weapon system. Section 5 summarizes the method of measuring structural robustness and how to choose the optimal weapon and equipment portfolio under the constraints of capabilities and budget. Section 6 uses the armored battalion as an example to verify the feasibility of the method.

3. Problem description and analysis

3.1 Weapon system portfolio selection problem description

Let $W = \{w_1, w_2, \cdots, w_n\}$ be a set of weapons and equipment that can be selected for development. Each equipment added to the original combat network will affect the combat system and cause the change of the combat network structure. In the selection of a suitable equipment portfolio $P = \{w_i \in W\}$, the structural survivability is maximized, but at the same time, budget constraint C and capability constraint A need to be considered. Thus, in this paper, the goal of the weapon system portfolio selection problem is choosing a set of weapon system that maximizes the survivability of the network under the constraints of capabilities and budget limitations.

3.2 Problem analysis

There are several difficulties in solving the problem of choosing the weapon system portfolio based on indestructibility.

3.2.1 System modeling

NCW is evolving into “multi-domain warfare”, which aims to break the boundaries between services and domains and expands joint combat capabilities in the fields of land, sea, air, space, electricity, and network. So as to achieve synchronous cross-domain fire control and global maneuvering, and seize the advantages of the physical domain, cognitive domain and time [38,39]. Weaponry system modeling also has certain difficulties in fully considering “one network and five domains”. Therefore, this article focuses on static structural indestructibility indicators, mainly considering the correlation between equipment and equipment attributes. According to the operation loop theory, the equipment is classified into different functions, and the combat network model is established.

3.2.2 Index selection

A weaponry system demonstration is a very complicated issue. Its evaluation involves the core combat technology indicators of single equipment, the contribution rate of single equipment to the system, combat effectiveness, structure, confrontation, and other aspects. This paper only considers the aspect of structural invulnerability. Most scholars use the simulation method to study the invulnerability of complex networks, which determines that the accuracy of the invulnerability is closely related to the scale of the network and the number of simulations, with great stability. In order to solve the problems of computational complexity and measurement accuracy of the invulnerability measure of a complex network, this article uses the comprehensive evaluation index of the operation loop, that is, the method of natural connectivity. It starts from the internal attributes of the complex network and has good analytical capabilities and can objectively characterize the survivability of complex networks.

4. Modeling of weapon system combat network

Before selecting a weapon system combination, the first task is describing the weapon system in a scientific and logical way. Based on the choice of equipment system combination for structural invulnerability, only two layers of the network are considered, namely the logic layer network and the attribute layer network.

4.1 Logic layer network modeling description

The logic layer network is a description of the relationship between the logical interactions of equipment. It is related to the cognition of the modeler. It is a static relationship and represents the functional structure of the entire equipment system. This article uses the operation loop to describe the weapon equipment system, abstracts the relationship between equipment and equipment into nodes and edges.

4.1.1 Combat node

The operation loop is the foundation and core of the entire system's networked modeling method, and the theoretical basis proposed by the concept of the operation loop is the theory of operation loops. The operation loop theory is a theory proposed by American military strategist and Air Force colonel John Boyd in the 1970s based on his one-on-one air combat experience. Boyd et al. [40] decomposed one of our combat operations against the enemy into four processes: observe, orient, decide and act, forming a operation loop, or OODA (observation orientation decision action) loop.

According to the OODA loop theory, the combat process is a continuous loop process. According to the process of the OODA loop, Cares et al. [41] proposed the concept of a operation loop. It is believed that during the OODA loop, equipment will also form a directed closed loop. The closed-loop is the operation loop, and the adjacency matrix is used to represent the relationship between the equipment.

According to the operation loop theory, Zhang et al. [42] proposed that the combat loop is a closed loop formed by the scout, decision, impact weapons and enemy target entities in order to complete specific combat tasks. A basic operation loop is shown in Fig. 1. It indicates a basic combat process, that is, the scouting equipment finds the enemy target, and uploads the information to the decision equipment, the decision equipment makes a decision to issue a fire attack order on the impact equipment, and finally affects the equipment to fire the enemy target [43].

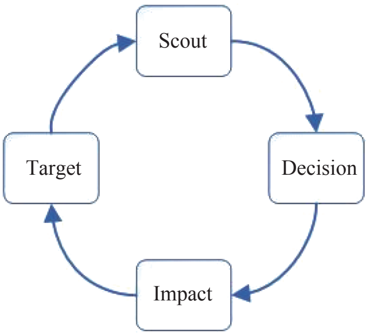


Fig. 1 A basic operation loop

According to the operation loop theory, nodes can be divided into scout nodes, decision nodes, impact nodes and target nodes. $V_1 = \{V_S, V_D, V_I, V_T\}$ represents the set of combat network nodes, where $V_S = \{v_{S_1}, v_{S_2}, \cdots, v_{S_s}\}$ represents the set of scout nodes, $V_D = \{v_{D_1}, v_{D_2}, \cdots, v_{D_d}\}$ represents the set of decision nodes, $V_I = \{v_{I_1}, v_{I_2}, \cdots, v_{I_i}\}$ represents the set of impact nodes, $V_T = \{v_{T_1}, v_{T_2}, \cdots, v_{T_t}\}$ represents the set of target nodes, $N = S_s + D_d + I_i + T_t$ represents the total number of nodes.

A scout node is an equipment that performs reconnaissance, information collection, and early warning on the battlefield and targets in the course of combat. The decision node is the equipment that analyzes the collected information and issues instructions to other equipment. Impact node is equipment that obeys orders to strike and interfere with enemy targets. The target node includes all the target equipment of the enemy.

4.1.2 Combat relationship

The four types of nodes are arranged and combined, and there are 16 connection relationships between nodes. As shown in Table 1.

Table 1 Node connection mode in combat network

Node type	S	D	I	T
S	$S \to S$	$S \to D$	$S \to I$	$S \to T$
D	$D \to S$	$D \to D$	$D \to I$	$D \to T$
I	$I \to S$	$I \to D$	$I \to I$	$I \to T$
T	$T \to S$	$T \to D$	$T \to I$	$T \to T$

However among the 16 kinds of connection relationships, some connection relationships do not conform to actual combat scenarios or have a low probability of occurrence. For example, the impact equipment will not perform fire strikes and interference on the equipment, so $I\to S$, $I\to D$ and $I\to I$ are not consistent. After screening, the seven types of edge connection relationships shown in Table 2 and their specific meanings are obtained.

Table 2 Meaning of edge connection

Edge type	Meaning
$T\to S$	Scout equipment detects enemy targets.
$S\to S$	Information shares between two scout equipment.
$S\to D$	The scout equipment uploads the detected intelligence to the decision equipment.
$D\to S$	The decision equipment issues instructions to the scout equipment.
$D\to D$	Information shares between the two decision devices or one part gives instructions to the other.
$D\to I$	The decision equipment issues orders to the influence equipment.
$I\to T$	The influence equipment fires or interferes with enemy targets.

According to the edge connection relationship between nodes, we can use (1) to indicate whether there is a directed edge from node v_i to v_j, where $e_{ij}=1$ indicates that there is a directed edge from node v_i to node v_j; otherwise $e_{ij}=0$ indicates that there are no directed edges from node v_i to node v_j.

$$e_{ij}=\begin{cases}1, & \text{There are directed edges from } v_i \text{ to } v_j\\ 0, & \text{There is no directed edge from } v_i \text{ to } v_j\end{cases} \tag{1}$$

where $1\leqslant i,j\leqslant N$.

Through the above analysis, the logic layer network of the equipment system can be described as

$$G_l=(V_l,E_l)$$

where $E_l=\{e_{ij},1\leqslant i,j\leqslant N\}$ is a set of directed edges that represents the relationship between equipment.

4.2 Attribute layer network modeling description

The choice of equipment system combination has certain requirements on the ability of equipment. The capability index of equipment is related to its own attribute parameters and performance indexes. In fact, there is a certain mutual relationship between attributes, that is, the index system should be a network structure. For example, the accuracy of target positioning of reconnaissance equipment has an impact on the overview of damage to combat equipment.

In the indicator layer network, each attribute corresponds to a node in the network, and the existence of an influence relationship between attributes means that there are edges between nodes. For example, there are directed edges from target positioning accuracy to damage probability.

The equipment system index layer network can be described as

$$G_z=(V_z,E_z)$$

where $V_z=\langle V_{zS},V_{zD},V_{zI},V_{zT}\rangle$ represents a collection of equipment indicators. V_{zS} is a scout index, including attribute nodes such as reconnaissance range, scanning frequency, target recognition accuracy, target recognition probability, target positioning accuracy and reconnaissance speed. V_{zD} is a decision indicator, and the attribute nodes included are early warning time, false alarm rate and response time. V_{zI} is an influence index, and the attribute nodes included are hit accuracy, intercept probability, damage probability, kill radius, maneuvering speed, interference power and ammunition quantity. V_{zT} is the target index, and the attribute nodes included are interference coefficient, protection coefficient, maneuvering speed, early warning time and reconnaissance capability. And E_z represents the association relationship between the attributes.

4.3 Network modeling of weapon equipment system

The weapon system network can be described as

$$G=(G_l,G_z)=((V_l,E_l),(V_z,E_z)).$$

The equipment system network is shown in Fig.2.

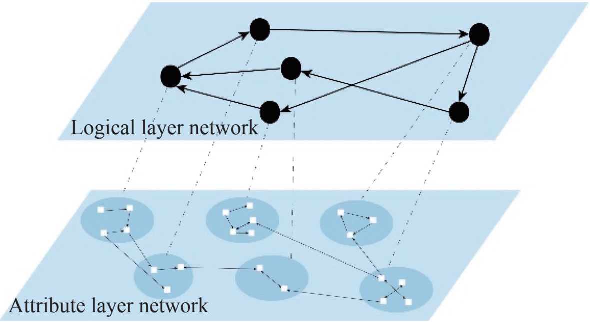


Fig. 2 Two-layer heterogeneous network

Abstracting the weaponry system as a network containing the system's constituent elements and the relationships between the elements is the basis of the entire solution process and directly determines the authenticity and effectiveness of the network model.

5. Weapon system portfolio selection based on combat networks

According to the constructed combat network model, the structural robustness of the weapon equipment system is measured, and the equipment system portfolio is selected based on this.

5.1 Operation loop comprehensive evaluation index

In a weaponry combat network, the number of operation loops represents a variety of ways to attack enemy targets. The greater the number of operation loops, the greater the number of ways to attack enemy targets. On the other hand, the greater the number of operation loops, the higher the redundancy of alternative combat approaches, and the stronger the survivability of the network [42,44]. Therefore, the number of operation loops can be used as a measure of the invulnerability of a functional combat network. However, when the combat network contains a large number of combat nodes and the edge relationship between the combat nodes is complicated, it becomes very difficult to accurately calculate the number of operation loops in the combat network. In order to quickly and easily calculate the number of operation loops in the combat network, we have introduced an index called the operation loop comprehensive evaluation index (OLCEI) to measure the structural robustness of the weapon equipment system, which can sensitively reflect the operation loops in the system combat network change in number [14]. The calculation process is as follows:

$$S=\sum_{i=1}^{N}\sum_{k=0}^{\infty}n_i^k=\sum_{k=0}^{\infty}\sum_{i=1}^{N}n_i^k=\sum_{k=0}^{\infty}n_k \tag{2}$$

where n_k represents the number of closed paths from node i as the starting point and endpoint as k. S indicates that there are more combat methods in the combat network and more alternative approaches. To ensure that S does not diverge, the length of the ring needs to be weighed when calculating the number of operation loops:

$$S=\sum_{k=0}^{\infty}\frac{n_k}{k!}=\sum_{k=0}^{\infty}\sum_{i=1}^{N}\frac{\lambda_i{}^k}{k!}= \\ \sum_{i=1}^{N}\sum_{k=0}^{\infty}\frac{\lambda_i{}^k}{k!}=\sum_{i=1}^{N}\mathrm{e}^{\lambda_i}. \tag{3}$$

From (3), it is worth noting that S will be a large number with the increase of N. Therefore, define the OLCEI:

$$\bar{\lambda}=\ln(S)=\ln\left(\sum_{i=1}^{N}\mathrm{e}^{\lambda_i}\right). \tag{4}$$

5.2 Equipment system portfolio selection

This article considers capability constraints and costs constraints while pursuing the goal of the largest comprehensive evaluation index for functional combat network operation loops.

(i) Cost constraints. In the current global economic downturn, the tightening of national defense budgets is a general trend. It is impossible to indiscriminately develop a large number or even repeated weapons. Therefore, the cost of the equipment combination to be developed cannot exceed the budget.

(ii) Capability constraints. In the actual combat process, the main purpose is to make the enemy's target incapable of combat capability, so it is necessary to ensure that each basic capability meets the needs.

Assume that $W=\{w_1,w_2,\cdots,w_n\}$ is a set of weapons and equipment that can be selected for development. When choosing a weapon and equipment combination P, we must first consider its budget, that is

$$P=\left\{w_i\in W\middle|\sum C(w_i)\leqslant C\right\}. \tag{5}$$

Secondly, to meet the capability constraints, this paper considers the scouting capability (AS), the decision capability (AD), and the impact capability (AI) to meet the target needs to be based on the operation loop theory, that is, P simultaneously meets

$$P=\left\{w_i\in W\middle|\sum A(w_i)\geqslant A\right\}. \tag{6}$$

Finally, the cost-benefit ratio of the weapon and equipment combination that meets the above constraints is maximized to obtain the optimal weapon and equipment combination.

$$R=\frac{\bar{\lambda}}{\sum C(w_i)} \tag{7}$$

Therefore, the combination optimization idea in this paper is to obtain a selectable equipment set after considering the capability constraint (A) and cost constraint (C) for candidate equipment with different functions to be developed. Taking into account the constraints will greatly reduce the possibility of combining different equipment. Then add the selectable equipment sets to the original equipment system, and compare the cost-benefit ratio of different new equipment systems. Finally, the optimized optimal equipment system is obtained. The combined optimization process is shown in Fig.3.

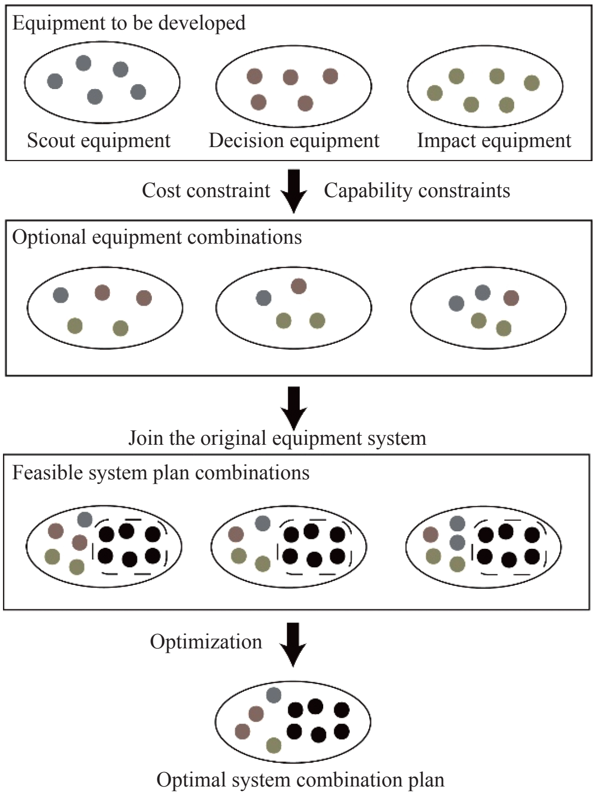


Fig. 3 Process of combinatorial optimization

6. Case study

The armored synthetic battalion integrates scout, decision, and impact, and can perform some complex tasks alone. It has system characteristics and can be regarded as a small equipment system. To verify the feasibility of the above methods, this article uses the armored synthetic battalion as an example to explore the choice of weapon and equipment combination based on structural robustness.

6.1 Case description

Assuming that country A and country B are hostile, country A decides to launch an armored battalion to attack country B's main battle tanks, gunships, infantry fighting vehicles, anti-tank guns, and command centers. The weapons and equipment contained in the armored synthetic battalion system of country A and their functions are shown in Table 3, which mainly considers the combat unit.

Table 3 Armor synthesis battalion system equipment composition

Equipment	Quantity	Classification of meta-function nodes		
		Scout	Decision	Influence
Armored command vehicle	1	√	√	√
Command tank	1	√	√	√
Main battle tank	12	√	√	√
Infantry fighting vehicle	6	√	√	√
Armored frontier observation command vehicle	1	√	√	
Self-propelled howitzer	4			√
Low-altitude search and warning radar vehicle	1	√		
Self-propelled artillery	4			√
Armored reconnaissance vehicle	2	√		
Drone	1	√		
Reconnaissance intelligence processing vehicle	2	√	√	
Reconnaissance attack helicopter	1	√		√

Armored command vehicles have the capabilities of scout, decision, and impact on the enemy, that is, they can simultaneously serve as a scout, decision, and impact nodes in the combat network, but are mainly used for combat command of the whole battalion in combat. Command tanks are mainly used for combat command of main battle tanks.

All the main battle tanks are a tank company, and the company has three tank platoons. The first three tank platoons arrange one main battle tank for the battle command under the control of four main battle tanks, and the last platoon has two main battles. The tank is used for maneuvering.

All infantry fighting vehicles are a loading company, and the company has two infantry platoons. Each platoon is equipped with one infantry fighting vehicle for combat command and has two infantry fighting vehicles. The howitzer company has an armored forward-looking observation vehicle for combat command, and four self-propelled howitzers for fire strike.

The anti-aircraft artillery company has a low-altitude search and warning radar vehicle for reconnaissance, a reconnaissance intelligence processing vehicle for reconnaissance and operational command, and four self-propelled anti-aircraft artillery for fire strike.

The intelligence company has two armored reconnaissance vehicles and one drone for reconnaissance, one reconnaissance intelligence reconnaissance vehicle for command, and one reconnaissance attack helicopter for combat protection. The structure is shown in Fig. 4.

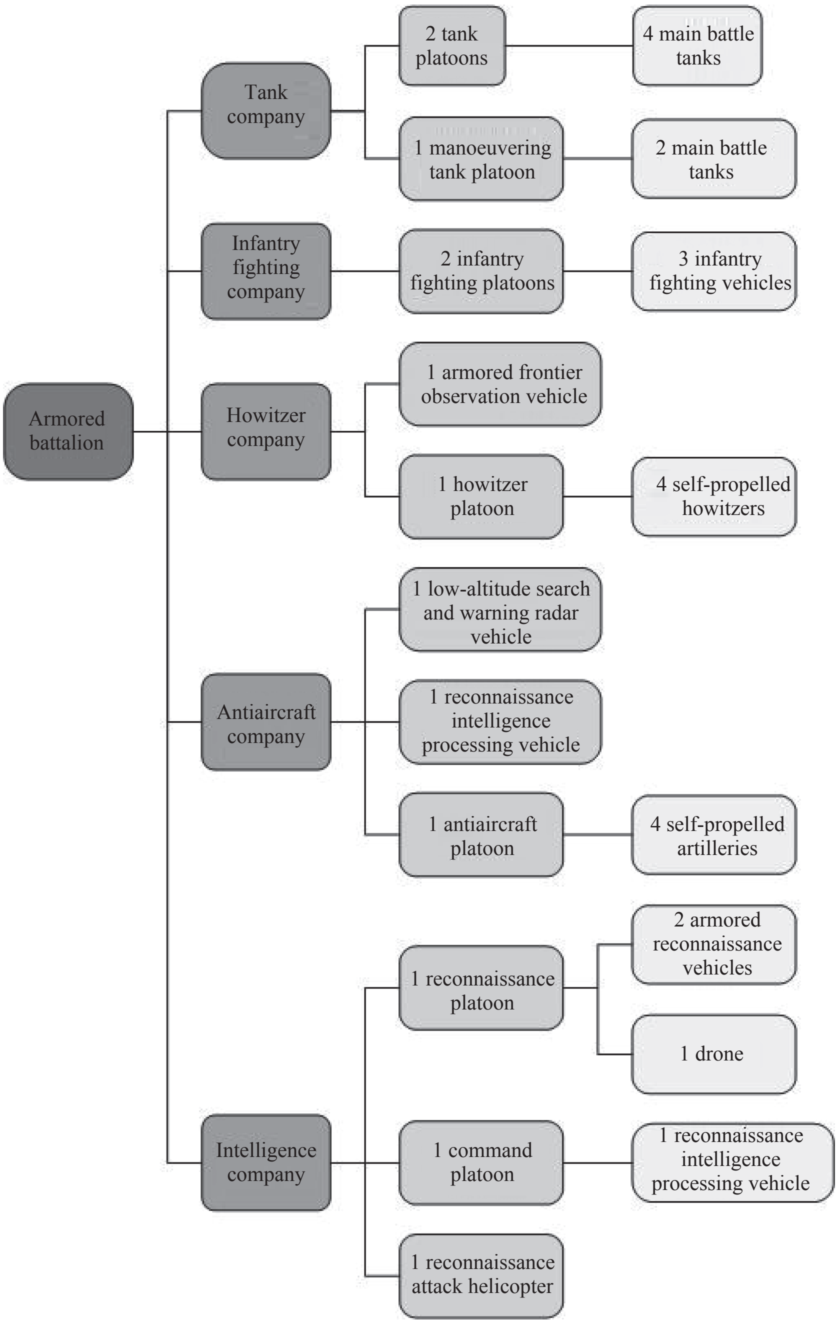


Fig. 4 Composition of digital armor synthesis battalion

From the above battalion structure, it can be seen that there are some shortcomings, for example, too few operational commands for the whole battalion may cause too late decision-making and too few helicopters used by the intelligence company for protection. Therefore, it is necessary to develop a batch of equipment to join the original armor synthesis camp, so that the system's damage resistance must be increased. Due to the limited budget, it is impossible to develop all equipment, so it is necessary to strike a balance between indestructibility, budget, and capabilities. Table 4 shows the data indicators of the equipment to be developed related to the equipment synthesis battalion system. The data used in this article are all confidential data after considering the influence relationship between attributes. Taking the armored reconnaissance vehicle as an example, it has both scout and impact functions during the battle and does not have a decision function. The functional capability value is described as 1 to 10, and the capability values are 7 and 5 respectively; at the same time, the cost is 1. The 1 to 10 characterization indicates that it takes 7 unit values to develop an armored reconnaissance vehicle.

Table 4 Equipment to be developed

Equipment	Quantity	Sign	Scout capability	Decision capability	Impact capability	Cost
Armored command vehicle	1	*A*	4	7	5	10
Self-propelled howitzer	2	*B*	—	—	7	5
Self-propelled artillery	2	*C*	—	—	5	5
Armored reconnaissance vehicle	1	*D*	7	—	5	7
Drone	1	*E*	9	—	—	6
Reconnaissance intelligence processing vehicle	1	*F*	8	6	—	7
Reconnaissance attack helicopter	2	*G*	7	—	8	9

Table 5 lists the requirements for basic functions and budget constraints. For confidentiality reasons, these values are specially treated. The minimum requirement for the scout capability is 20 units, the minimum requirement for the decision capability is 10 units, and the minimum requirement for the impact capability is 25 units. The budget provided cannot exceed 45 units.

Table 5 Restrictions

Scout capability	Decision capability	Impact capability	Cost
20	10	25	45

6.2 Calculation process

This section will show the actual calculation process of the weapon system combination selection.

6.2.1 Combat network construction

The equipment of *A* and *B* are abstracted as nodes, and the relationship between the nodes and the edge of the nodes is established according to the operational scenario described in Fig. 4 to construct a schematic diagram of the combat network, as shown in Fig. 5. Among them, purple represents the tank company, pink represents the armored company, light green represents the howitzer company, red represents the armored command vehicle, brown represents the antiaircraft company, dark green represents the intelligence company, and yellow represents the enemy target.

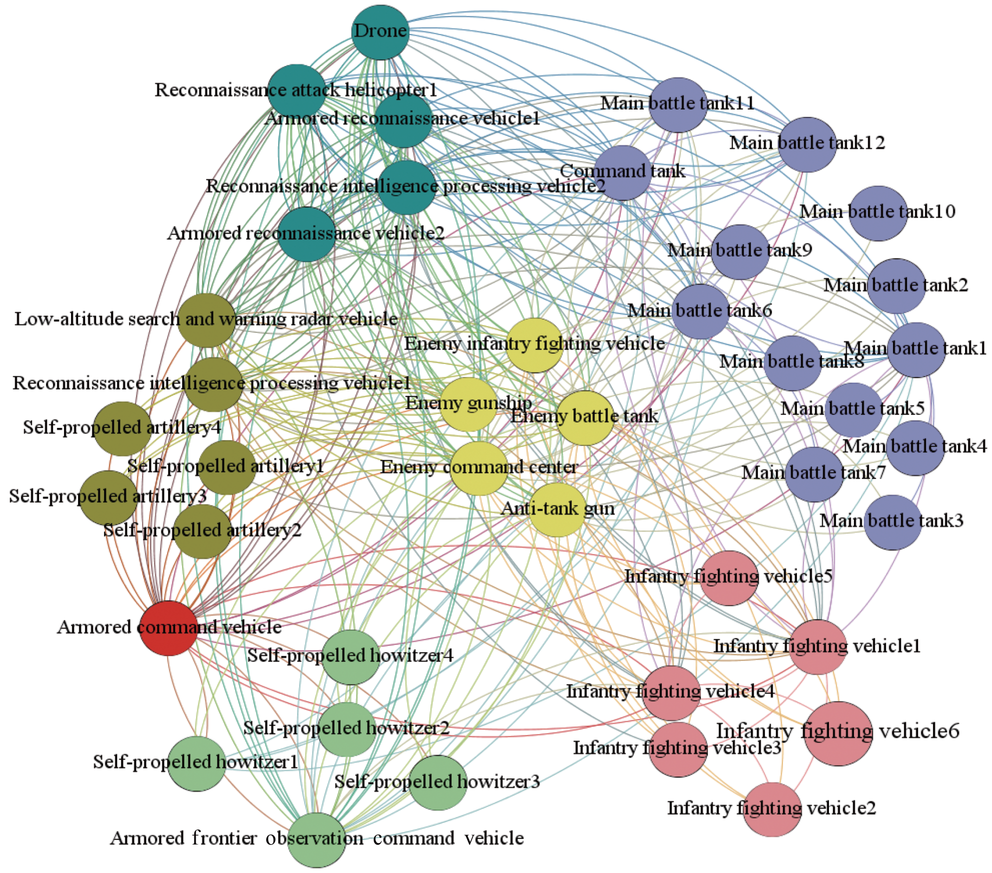


Fig. 5 Schematic of armored battalion combat network

6.2.2 Equipment combination selection

According to the budget and capacity constraints, the feasible equipment combinations are screened, with a total of 14 groups.

For example, $P_1 = \{A, B, C, E, F, G\}$. After joining the original equipment combat system, the combat network changes. The schematic diagram of the changed combat network is shown in Fig. 6. The larger nodes are newly added equipment.

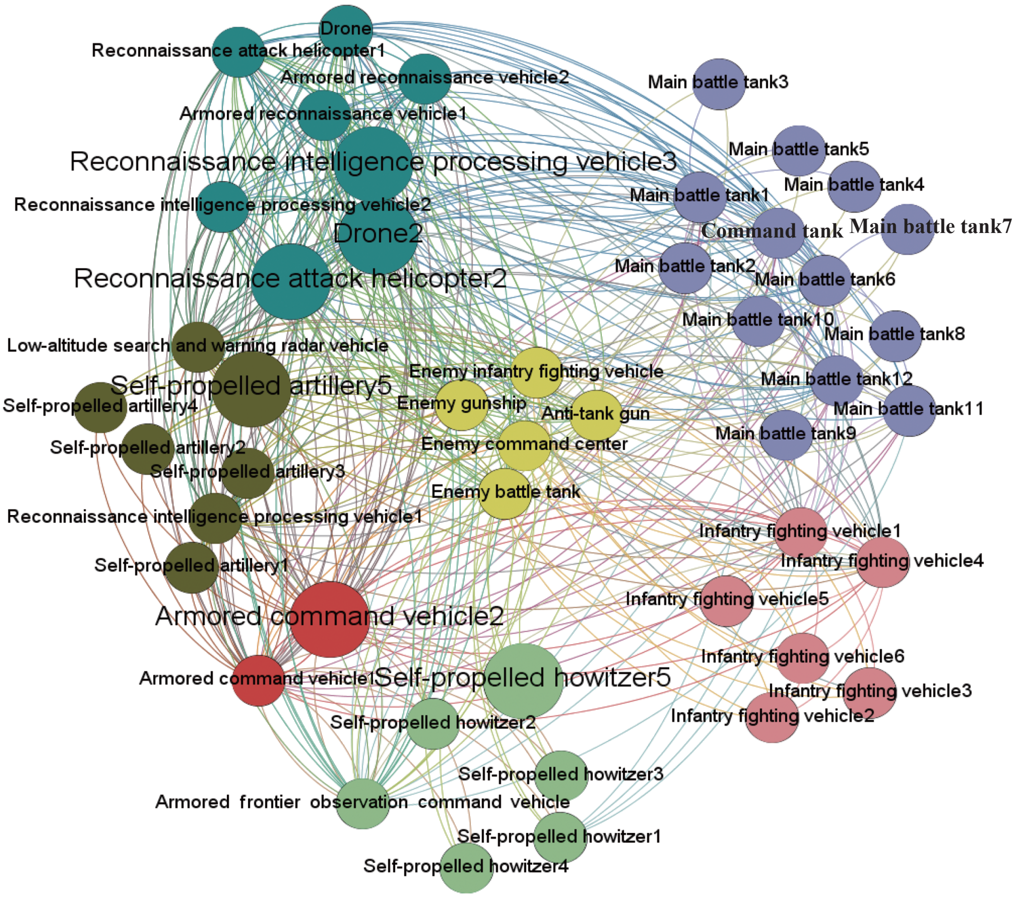


Fig. 6 Combat network after joining P_1

The equipment in the P_1 combination has a reconnaissance capability of 4 + 9 + 8 + 7 = 28, an accusation capability of 6 + 7 = 13, an impact capability of 5 + 7 + 5 + 8 = 25, a cost of 10 + 5 + 5 + 6 + 7 + 9 = 42; all four indicators meet the constraints.

After satisfying the constraints, the combat network integrated with the new equipment combination is calculated for the comprehensive evaluation index of the combat network operation loop. The eigenvalues are extracted from the adjacency matrix corresponding to the new combat network. Using the formula introduced in Section 4, the P_1 damage resistance is 15.133 34. Finally, calculate its cost-effectiveness ratio:

$$R = \bar{\lambda} / [C(w_A) + C(w_B) + C(w_C) + C(w_E) + C(w_F) + C(w_G)] = \frac{15.133}{42} = 0.36. \tag{8}$$

Thus P_1 could be one of the alternatives. Based on the above calculation process, all other scheme portfolios that meet the constraints are calculated as shown in Table 6.

It is obvious from Table 6 that the P_{11} scheme combination $\{A, D, F, G, G\}$ is the best in terms of damage resistance and cost-effectiveness ratio, and it is the last equipment combination to join the original armor synthesis camp. The more abilities a piece of equipment has, to a certain extent, the connection it can have with other equipment is stronger than the equipment containing only a single ability, and the number of edges it connects will be relatively large. For example, the five types of equipment in P_{11} can exert two kinds of capabilities. After joining the original equipment system, it can be connected with more equipment in the original system, making the system more closely integrated, and creating more combat loops. This will greatly enhance the survivability of the combat network and conform to reality significance, to a certain extent verified the feasibility of the method.

Table 6 All weapons and equipment portfolios that meet the constraints

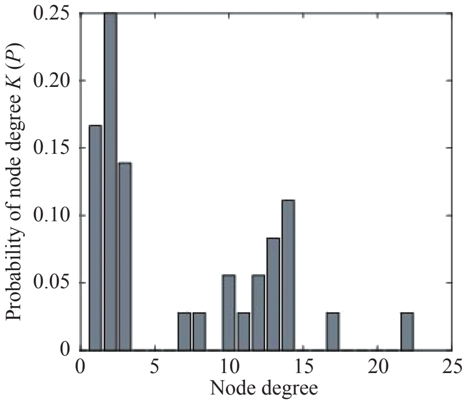
Sign	Equipment portfolio	Scout capability	Decision capability	Impact capability	Cost	Structural robustness	Cost-benefit ratio
1	*A, B, C, E, F, G*	28	13	25	42	15.133 34	0.360 318
2	*A, B, B, E, F, G*	28	13	27	42	15.130 09	0.360 24
3	*A, B, D, E, F, G*	35	13	25	44	15.938 09	0.362 229
4	*A, B, B, C, C, E, F*	21	13	29	43	15.158 08	0.352 513
5	*A, B, B, C, D, E, F*	35	13	29	45	15.960 87	0.354 686
6	*A, C, F, G, G*	26	13	26	40	15.256 94	0.381 423
7	*A, C, C, F, G, G*	26	13	31	45	15.270 75	0.339 35
8	*A, B, C, F, G, G*	26	13	33	45	15.267 48	0.339 277
9	*A, B, F, G, G*	26	13	28	40	15.253 65	0.381 341
10	*A, B, B, F, G, G*	26	13	35	45	15.264 21	0.339 205
11	***A, D, F, G, G***	**33**	**13**	**26**	**42**	**16.060 74**	**0.382 399**
12	*A, C, C, D, F, G*	26	13	28	43	14.960 06	0.347 908
13	*A, B, C, D, F, G*	26	13	30	43	14.957 77	0.347 855
14	*A, B, B, D, F, G*	26	13	32	43	14.955 49	0.347 802

6.3 Results analysis

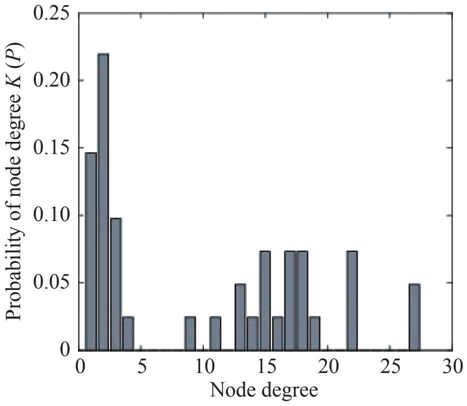
For complex networks, the degree distribution fully reflects the structural invulnerability of the network to a certain extent. In order to further verify the effectiveness of the model, this paper compares the degree distribution changes of the original network and the network with P_{11} equipment combined.

Under the same conditions, the more uneven the network degree distribution, the stronger the invulnerability of the network. The degree distribution of the two networks is shown in Fig. 7. It can be clearly seen that the network degree after joining P_{11} is more uneven and more dispersed. To a certain extent, it shows the improvement of structural invulnerability.

At the same time, to further verify the superiority of the proposed model, it is compared with a model composed of traditional complex network structure indicators related to invulnerability. In this paper, algebraic connectivity, network efficiency, and network structure entropy are selected as indicators to measure the network's invulnerability. These three indicators are based on graph theory and statistical physics and are comprehensive. Table 7 illustrates the values of the three traditional complex network indicators and OLCEI and the respective cost-effectiveness ratios. The maximum value of each column is marked in red.



(a) Original network degree distribution



(b) Network degree distribution after adding P_{11} equipment combination

Fig. 7 Comparison of degree distribution

Table 7 Index value under different models

Sign	Algebraic connectivity		Network efficiency		Network structure entropy		OLCEI	
	Value	Cost-benefit ratio	Value	Cost-benefit ratio	Value	Cost-benefit ratio	Value	Cost-benefit ratio
1	1.033 2	0.024 6	0.524 2	0.012 481	3.514 2	0.083 671	15.133 34	0.360 318
2	1.033 4	0.024 605	0.523 8	0.012 471	3.511 4	0.083 605	15.130 09	0.360 24
3	1.034 8	0.023 518	0.535 4	0.012 168	3.521 7	0.080 039	15.938 09	0.362 229
4	1.030 1	0.023 956	0.513 6	0.011 944	3.539 3	0.082 309	15.158 08	0.352 513
5	1.031 3	0.022 918	0.524 3	0.011 651	3.546 2	0.078 804	15.960 87	0.354 686
6	1.034 2	0.025 855	0.613 3	0.015 333	3.589 1	0.089 728	15.256 94	0.381 423
7	1.032 6	0.022 947	0.579 2	0.012 871	3.570 1	0.079 336	15.270 75	0.339 35
8	1.032 5	0.022 944	0.578 9	0.012 864	3.567 4	0.079 276	15.267 48	0.339 277
9	1.034 3	0.025 858	0.614 1	0.015 353	3.587 3	0.089 683	15.253 65	0.381 341
10	1.032 8	0.022 951	0.578 5	0.012 856	3.564 5	0.079 211	15.264 21	0.339 205
11	1.035 7	0.024 660	0.626 2	0.014 910	3.613 3	0.086 031	16.060 74	0.382 399
12	1.032 9	0.024 021	0.576 5	0.013 407	3.572 1	0.083 072	14.960 06	0.347 908
13	1.032 8	0.024 019	0.576 2	0.013 4	3.569 2	0.083 005	14.957 77	0.347 855
14	1.033 2	0.024 028	0.575 8	0.013 391	3.566	0.082 93	14.955 49	0.347 802

It can be seen from Table 7 that the four indicators used to measure the invulnerability of the P_{11} equipment combination are the largest of all equipment combinations. To a certain extent, it shows that OLCEI has a certain accuracy for measuring the invulnerability of the network. However, in the cost-effectiveness ratio after considering the cost, the optimal equipment combination of algebraic connectivity, network efficiency, and network structure entropy has changed, resulting in deviations in the results. However, under the condition of meeting the cost constraints, the stronger the destruction resistance of the natural network, the better. Obviously, P_{11} is more suitable for development. Therefore, these four indicators have a certain consistency in evaluating the invulnerability of the network, but when considering the cost at the same time, SWSPS based on OLCEI will be more suitable.

7. Conclusions

The choice of weapon system combination is part of the development planning of weapons and equipment, and it is of great significance for whether it can have an advantage in a future military confrontation. In actual operations, in addition to paying attention to the extent of our fire attack on the enemy, we must also pay attention to the stability of our structural system when the enemy attacks us. Therefore, this paper takes structural damage resistance as the goal, constructs a combat network model from the system level, uses the idea of the operation loop to quantitatively measure the damage resistance, and pursues a balance between goals, capabilities, and budget constraints.

The method proposed in this paper has the following advantages: (i) fully consider the interrelationship between equipment and equipment, the relationship between equipment attributes at the system level to establish a two-layer heterogeneous combat network model; (ii) use the operation loop comprehensive assessment index to combat destructive measures, starting from the internal attributes of complex networks describe the redundancy of alternative pathways in the network; (iii) consider the capacity requirements and cost budget to maximize the invulnerability of the entire weaponry system structure. Through the method of this article, we find that in the choice of equipment combination, the goal is structural damage resistance, not the more equipment developed, the better, but the richer the relationship between equipment and equipment, the more its functions, and the bigger the impact on the architecture .

WSoS demonstration is a very complicated system engineering and involves many aspects of scientific issues, including military requirement demonstration analysis, WSoS architecture designment, operational capability evaluation, operational effectiveness simulation evaluation, weapon system portfolio selection, weapon contribution rate analysis, and so on. Due to the complexity of the equipment system demonstration, there are still many deficiencies in the work of this paper. For example, this article only considers one target of destruction resistance, and the actual combat process is a multi-objective decision-making process. In addition, the consideration of constraints is not comprehensive. Weaponry operation is a dynamic process. Some equipment may be eliminated or updated over time, and this article only considers static operations, so there is still much work to be done. In the follow-up research, it is necessary to comprehensively consider other factors such as combat capability, technological maturity and other multi-target combination selections, dynamic modeling and analysis of combat networks, and non-combat units such as support equipment.

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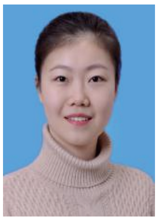
Biographies



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