Contemporary Mathematics
https://ojs.wiserpub.com/index.php/CM/

Research Article

Research on Capability Evaluation and Key Node Identification Method of Combat System

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Received: 20 May 2025; **Revised:** 4 July 2025; **Accepted:** 4 July 2025

Abstract: The assessment of combat system capabilities and the identification of critical nodes are focal points in the research of combat systems. This paper investigates the issue of identifying critical nodes within combat systems based on the construction of a combat system model and capability assessment. It proposes a method for constructing a combat system network model based on the number of connections between nodes, taking into account the impact of combat time on system capabilities. A time efficiency coefficient is introduced to develop a capability assessment model that incorporates time efficiency. Furthermore, a method for identifying critical nodes based on effectiveness betweenness centrality is proposed. Simulation results indicate that the combat system network model and capability assessment methods presented in this paper are valid, and the accuracy of the critical node identification method based on effectiveness betweenness centrality is high.

***Keywords*:** combat system network, combat capability assessment, time efficiency, key node identification, efficiency betweenness centrality

MSC: 93A30

1. Introduction

The modern combat system spans the distance and information transmission constraints, forms close cooperation, and has the characteristics of diverse and complex combat forces. Rapid and accurate identification of key nodes is of great significance to the construction of the combat system and the victory of the war.

In terms of combat capability evaluation, there are mainly two types of methods: one is the traditional evaluation methods, such as Availability-Dependability-Capability (ADC) model [1], Lanchester equation [2], fuzzy evaluation [3], evidence theory [4], which are suitable for simple structural problems, but are no longer applicable to combat system evaluation; the other is the evaluation method based on complex networks, which is widely used and highly recognized. Literature [5] proposes a combat capability evaluation model of the kill network based on the number of kill chains and target weights; Literature [6] proposes the uncertain self-information of the combat ring, and evaluates the effectiveness of the combat ring and the combat system based on improved information entropy; Literature [7] constructs the kill chain

DOI: https://doi.org/10.37256/cm.6420257271

capability model and the system kill chain capability model based on the attributes of combat nodes; Literature [8] uses information entropy to uniformly calculate the weight of the combat network edge, and then weights and sums to obtain the combat system measurement method.

There are three main methods for identifying key nodes in the network of the combat system: First, the key nodes are identified by fusing the complex network structure parameters, but the heterogeneity of the combat system is not considered. Literature [9] fuses the dielectric number and degree parameters to propose the centrality of the medium; Literature [10] improves the multi-attribute decision-making method fuses multiple structural parameters to evaluate the importance of Tor network nodes; the second is to use the node contribution rate to traverse each combat node to identify key nodes, which is suitable for small combat system networks. Literature [11, 12] construct a combat system network and capability evaluation model, and use the system contribution rate method to obtain the system contribution rate of each node; the third is to use Topsis, weighted sum, information entropy and other methods to build a node importance evaluation model, fusing functional attributes and network structure attributes as a measure. Literature [13] proposes a node importance index system, using entropy weight method and Topsis method to identify key nodes; Literature [14] combines multiple network structures and node attribute values to identify node importance by weighted summation method; Literature [15] proposes that the combat ring is uncertain self-information, and evaluates the effectiveness of the combat system based on improved information entropy, and constructs models to evaluate node importance from various aspects.

Analyzing the research status of combat system capability assessment and key node identification, the following problems are found:

1. The capability evaluation method of the combat system based on complex network is better than the traditional method, but the impact of combat time on the capability is not considered;

2. The key node identification method is mainly analyzed from two aspects: network structure and combat capability, but the method that comprehensively considers the two factors is not appropriate, and it is mainly based on weighted summation and Topsis, so it is necessary to find a more suitable method;

3. When identifying key nodes by calculating the system contribution rate of combat system nodes, the ergodic method is accurate but complex, and is not suitable for large-scale networks.

In response to the above problems, this paper changes the traditional connection probability to generate network connection edges in the past, and determines the number of connection edges of the combat system; improves the calculation method of strike chain efficiency, introduces the time benefit coefficient, and proposes a time-effective strike chain efficiency calculation method; according to the idea of betweenness centrality, a key node identification method of the combat system based on the performance betweenness is proposed, and the accuracy of the method proposed in this paper is verified by simulation experiments.

2. Multi-layer network model of combat system

The combat system network is a complex combat system composed of multiple nodes and edges, in which nodes represent the combat forces existing in the combat system, mainly including decision node D, kill node K, Sensory node S, communication node I, and target node T. Edge represents the interaction between combat forces, mainly including command relationship, strike relationship, perception relationship, and information support relationship.

2.1 *Modeling of combat nodes*

2.1.1 *Decision node modeling*

Decision nodes refer to all levels of combat command institutions or commanders, intelligence command and control institutions or commanders, fire killing command institutions or commanders, support command institutions or commanders, etc., decision nodes can receive, send, analyze, and process various types of combat information, and have the ability to command, plan, coordinate, and control their own forces, namely:

$$Z_D = (d, c_d, t_d) \tag{1}$$

Among them, $d \in (0, 1)$ is the ability of the decision node to make correct decisions; $c_d \in (0, 1)$ is the ability of the decision node to reliably transmit information to other nodes; $t_d \in (0, \cdots)$, in seconds, is the time when the decision node receives the superior command or sensory information until the decision node responds to it and issues a command.

2.1.2 *Kill node modeling*

Kill nodes refer to the lethal forces that perform lethal combat tasks at all levels and types. Kill nodes can destroy various targets and have the ability to receive combat command information and battlefield information, namely:

$$Z_K = (k, c_k, t_k) \tag{2}$$

Among them, $k \in (0, 1)$ refers to the ability of the kill node to kill and destroy the target; $c_k \in (0, 1)$ refers to the ability of the kill node to receive information from the Sensory node, the decision node, and the communication node; $t_k \in (0, \cdots)$, in seconds, is the time consumed by the kill node from the start of receiving the killing command to the completion of the target killing.

2.1.3 *Sensory node modeling*

Sensory nodes refer to the sensory power that performs battlefield sensing and target information collection at all levels. Sensory nodes can Sensory the battlefield and target, and have the ability to provide target information guidance to kill nodes and provide battlefield information support for decision nodes, namely:

$$Z_S = (s, c_s, t_s) \tag{3}$$

$s \in (0, 1)$ refers to the ability of sensory nodes to sense target information such as location and type. In order to facilitate research and analysis, this paper believes that sensory ability has nothing to do with target characteristics and environmental factors; $c_s \in (0, 1)$ is the ability of sensory nodes to transmit target information to decision nodes, communication nodes, and kill nodes; $t_s \in (0, \cdots)$, in seconds, is the time consumed by sensory nodes to sense target information and complete information processing and information sharing.

2.1.4 *Communication node modeling*

Communication nodes refer to various types of communication support forces with communication support functions. Communication nodes can be used as a communication medium for other combat nodes to achieve communication between combat nodes, supporting the smooth operation of the combat network and the function of each node, namely:

$$Z_I = (c_I, t_I) \tag{4}$$

$c_I \in (0, 1)$ refers to the ability of communication nodes to transmit combat information with decision nodes, sensory nodes, and kill nodes; $t_I \in (0, \cdots)$ is the time consumed by communication nodes to complete information transmission from receiving information.

2.1.5 *Target node modeling*

The target node refers to the opposing party's combat system of the combat system, that is, our combat system. Because this paper focuses on the opposing party's combat system, it does not specifically distinguish the network node attributes of our combat system, but only makes an important distinction, namely:

$$Z_T = (w_k) \tag{5}$$

$w_k \in (0, 1)$ refers to the threat degree of the first target node to the opponent's combat system during the confrontation.

2.2 *Combat relationship edge modeling*

2.2.1 *Kill relation edge modeling*

The edge $e_{k \to t} \in (0, 1)$ of the killing relation refers to the edge of the kill node pointing to the target node, and the weight of the edge represents the damage ability of the kill node to the target node. In this paper, the damage ability of the kill node is equivalent to its own killing ability, regardless of the influence of target characteristics and environmental factors.

2.2.2 *Sensory relational edge modeling*

The edge $e_{t \to s} \in (0, 1)$ of sensory relation refers to the edge of the target node pointing to the sensory node, and the weight of the edge represents the detection ability of the sensory node to the target node. In this paper, the detection ability of the sensory node is equivalent to its own sensory ability, regardless of the influence of target characteristics and environmental factors.

2.2.3 *Information transfer relationship edge modeling*

The information transmission relationship edge $e_{i \leftrightarrow j} \in (0, 1)$ refers to the mutual transmission edge between decision nodes, sensory nodes, and communication nodes with information transmission capabilities. The weight of the edge represents the information transmission capabilities between nodes, and the weight calculation is as shown in Equation (6).

$$e_{i \leftrightarrow j} = c_i * c_j, \quad i, j \in (d, s, I) \tag{6}$$

$c_{i \leftrightarrow j}$ represents the information transmission capacity between combat nodes, and c_i and c_j represent the information transmission capacity of decision nodes, sensory nodes, or communication nodes.

2.3 *Combat system network generation*

From the existing relevant literature, it can be seen that there are two ways to generate the network of the combat system. One is to generate the network of the combat system according to the actual combat force and operating mechanism of the combat system [12], and the other is to compare the actual combat force of the combat system. According to experience, the connection probability between nodes is given to generate node connections [16]. In view of the limitations of the existing combat system network generation methods (complete replication method is difficult to implement, and the probabilistic edge method is not stable), this study proposes a network construction method based on the number of fixed edges, and builds a stable and controllable combat system network by setting the quantitative parameters of specific relationship edges, including five types of sub-networks.

2.3.1 *Building a decision network*

It is composed of decision nodes connected in both directions, and the number of edges is recorded as p_1. Increasing p_1 value can improve node cooperation ability and network stability, but it is restricted by factors such as decision efficiency and time cost.

2.3.2 *Building a kill network*

The number of edges is denoted as p_2. The value of p_2 reflects the multi-target killing ability of the kill node. The larger the p_2, the stronger the killing efficiency.

2.3.3 *Building sensory networks*

The number of edges is denoted as p_3. The p_3 value represents the multi-target detection ability of the sensory node, and the increase of p_3 directly improves the sensory coverage.

2.3.4 *Building a communication network*

It is composed of two-way connected communication nodes, and the number of edges is denoted as p_4. The increase of p_4 can enhance the stability of information transmission, but it needs to weigh the limitation of communication load and time cost.

2.3.5 *Building an information dependency network*

It is composed of four types of nodes: sensory, communication, decision, and kill. Five key connection parameters are defined: sensory → decision edge number p_5, sensory → kill edge number p_6, sensory → communication edge number p_7, communication → decision edge number p_8, communication → killing edge number p_9. Increasing the connection parameters can enhance the stability of the information network, but it needs to comprehensively consider constraints such as information transmission delay, node processing capacity, and system construction cost.

3. Key node recognition algorithm based on efficiency betweenness centrality

3.1 *Betweenness centrality*

Betweenness centrality was proposed and defined by Linton Freeman in 1977. It is an important index to measure the control ability of nodes over the flow of information in a network. Its core characterizes the pivotal role of nodes in the shortest path of the network: the higher the BC value of a node, the more the shortest path intermediary functions it bears in the network topology, and the stronger the control over information propagation. The calculation formula is shown in Equation (7).

$$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{7}$$

σ_{st} is the total number of shortest paths from node s to t, and $\sigma_{st}(v)$ is the number of shortest paths through node v.

3.2 *Efficiency betweenness centrality*

Aiming at the limitation of traditional Betweenness Centrality (BC) in the identification of key nodes in the combat system (ignoring the difference in kill chain effectiveness), this paper proposes the concept of Efficiency Betweenness Centrality (EBC). Its core improvement is to dynamically correlate the number of kill chains participated by nodes with the combat effectiveness on the chain, breaking through the static evaluation mode of BC only considering the number of paths. EBC represents the sum of the comprehensive combat effectiveness of all kill chains participated by nodes, and the mathematical expression is as shown in Equation (8).

$$EBC(v) = \sum_{d \neq v \neq t} \left(\frac{\sigma_{dt}(v)}{\sigma_{dt}} * \eta_{st} \right) \tag{8}$$

In the equation, σ_{dt} is the total number of kill chains from the node d to the node t, $\sigma_{dt}(v)$ is the number of kill chains passing through the node v, and η_{st} is the efficiency weight of a single kill chain.

3.3 *Search for battle system kill chain based on depth first search algorithm*

Based on the Depth-First Search (DFS) framework [17], a combat-oriented kill chain search method is proposed. The core innovation of the algorithm lies in the kill relation constraint mechanism, and its execution process pseudocode is as follows.

Algorithm 1 Strike Chain Search Algorithm
Input:
$G = (V, E)$: Operational system network
Output:
$YXl_{k \to t}$: All valid strike chains in the operational system network.
1. Find the strike relationship edges $e_{k \to t}$ between strike nodes and target nodes in G
2. Find all strike chains $l_{k \to t}$ in G that passes through strike relationship edges
3. Find the remove_node that needs to be removed in each strike chain
4. Exclude all invalid strike chains $l_{k \to t}$ containing remove_node, and obtain valid strike chains $YXl_{k \to t}$.

3.4 *Calculate kill chain efficiency*

In the combat system, multiple kill nodes are connected with decision nodes, sensory nodes, and target nodes to form a multi-class kill chain to the target. Each kill node is connected with different combat nodes, which can form multiple kill chains, and the kill efficiency of each kill chain is different. The greater the capability of the combat node, the less time it takes, and the higher the kill efficiency.

Based on the calculation method of kill chain efficiency proposed in literature [16], this paper improves the calculation method, adding the consumption time t and time coefficient γ of the whole process of combat chain operation to consider the impact of kill chain kill time on kill efficiency. The improved calculation formula is shown in Equations (9) and (10).

$$ksl_l = sk \prod_{i}^{n_d} d_i \prod e_{ab} * \frac{1}{\gamma t} \tag{9}$$

$$s = \max_{i=1}^{n_s}(s_i) \tag{10}$$

In the equations, ksl_l represents the efficacy of the l-th kill chain, s_i represents the detection capability of the i-th sensory node in the l-th kill chain, n_s represents the total amount of sensory nodes in the l-th kill chain, n_d represents the total amount of decision nodes in the l-th kill chain, e_{ab} is the weight of the relationship between nodes a and node b in the kill chain, including the edge weights of the sensory relationship, the edge weights of the kill relationship, and the information transmission edge weights. $\gamma \in (-\propto, +\propto)$ is the time efficiency relationship coefficient. The larger the time efficiency coefficient, the faster the efficiency of the kill chain decreases.

3.5 *Calculate the EBC of a node*

According to the concept of EBC, this paper proposes three methods for calculating the comprehensive efficiency of the kill chain. The first method is to sum the efficiency of the kill chain through nodes without considering the weight of the kill target, as shown in Equation (11).

$$E_i^1 = \sum ksl_l \tag{11}$$

This method directly sums the efficiency of all the kill chains passing through a specific node, and is suitable for cases where the priority or importance of killing targets is not distinguished. It can quickly estimate the basic contribution of nodes in the combat system.

The second is to consider the weight of the killing target and sum the efficiency of the kill chain through the nodes, as shown in Equation (12).

$$E_i^2 = \sum w_k ksl_l{}^k \tag{12}$$

On the basis of the first method, the killing target weight w_k is introduced to sum the efficiency of the kill chain of different targets. This method fully considers the importance difference of targets, makes the effectiveness evaluation closer to the actual combat needs, and can more accurately reflect the value of nodes in killing key targets.

The third is a comprehensive efficiency method that considers multiple kill chains to kill the same target, as shown in Equations (13) and (14).

$$ksl^k = 1 - \prod \left(1 - ksl_l^k\right) \tag{13}$$

$$E_i^3 = \sum w_k ksl^k \tag{14}$$

On the basis of the second method, this method further considers the situation that there are multiple kill chains when killing the same target. By weighting and summing the effectiveness of all kill chains against the same target, and then summing different targets, the comprehensive efficiency of nodes in the combat system is comprehensively evaluated, especially for the accurate measurement of the overall contribution of nodes in complex combat scenarios.

4. Evaluation criteria and algorithms

4.1 *Evaluation criteria*

In the analysis of combat system, identifying key nodes based on the contribution rate of combat system is considered to be the most accurate method [18]. This paper takes this method as the evaluation standard for the correctness of the proposed method, and evaluates the superiority of the proposed method from the following two key indicators.

4.1.1 *Key node identification method is time-consuming*

The time-consuming of the key node identification method is an important index to measure the computational efficiency of the method. It is expressed by T and obtained by counting the running time of the code. The shorter the time, the higher the efficiency of the method in the calculation and identification process, and the key information can be provided to decision makers in a shorter time. The proposed method in this paper significantly reduces unnecessary computational overhead by optimizing the algorithm structure and calculation steps when identifying key nodes, thus realizing fast identification. This not only improves the timeliness of combat decision-making, but also provides the possibility for real-time adjustment and optimization of the combat system.

4.1.2 *Kendall rank correlation*

It is used to measure the correlation between the algorithm ranking results and the key node ranking identified by the system contribution rate method, reflecting the consistency between the node ranking and the actual key node ranking, as shown in Equation (15).

$$\tau = \frac{p-k}{\frac{1}{2}n(n-1)} \tag{15}$$

p and k are the number of consistent pairs and inconsistent pairs, respectively. The higher the Kendall value, the closer the algorithm sorting is to the actual sorting, and the better the method effect.

4.2 *Combat system contribution rate identification key node method calculation of combat capability*

4.2.1 *Single kill node to single target*

When a single target kills a single kill node in the combat system, it is proposed to calculate the combat capability of multiple kill chains composed of the kill node as shown in Equation (16).

$$E_j{}^i = 1 - \prod^{n_l}(1 - ksl_j{}^i) \tag{16}$$

$E_j{}^i$, $ksl_j{}^i$, n_l represent the combat capability of the i-th kill node to the j-th target, the kill chain, and the number of kill chains, respectively.

4.2.2 *Calculation of combat capability of multi-kill nodes against single target*

When multiple killing nodes kill a single target in the combat system, the combat capability of multiple killing nodes against a single target is calculated as shown in Equation (17).

$$E_j = 1 - \prod^{n_k}(1 - E_j^i) \tag{17}$$

E_j, $E_j{}^i$ and n_k represent the combat capability, kill chain and the number of kill chains of all kill nodes in the combat system to the j-th target, respectively.

4.2.3 *Calculation of combat capability of multiple killing nodes against multiple targets*

The killing of multiple targets by multiple killing nodes is a comprehensive calculation of the effectiveness of all the killing chains of the combat system, that is, the combat system capability. Because different targets have different importance to the target system, the combat system capability calculation is shown in Equation (18).

$$E = \sum_{j=1}^{n_j} w_t E_j \tag{18}$$

where E represents the combat system capability, w_t represents the importance weight of the target, and n_j represents the number of target nodes.

4.2.4 *Combat system contribution rate calculation*

The contribution rate of the combat system refers to the degree of contribution of each system or element to the capability of the combat system in a specific combat system. The larger the contribution rate of the combat system, the more critical the corresponding nodes are. Combined with the evaluation method of the system combat capability in Equation (18), the calculation method of the contribution rate of the combat system is shown in Equation (19).

$$Q_i = \frac{E - E^{'}}{E} \tag{19}$$

In the formula, Q_i is the contribution rate of the combat system, and $E^{'}$ is the system capability after deleting nodes. The larger the contribution rate of the combat system, the more critical the corresponding node is.

5. Experiment and analysis

5.1 *Experimental environment and data*

In order to verify the feasibility and effectiveness of the proposed key node recognition algorithm based on performance betweenness, assuming that the red and blue sides engage in combat confrontation, the basic data of the blue side's combat system is given as shown in Tables 1-6, and the Python software and networkX data packet are used for experiments.

Table 1. Sensory node attributes

Sensory node	Sensory ability	Sensory information transmission ability	Sensory process time lag (min)
1	0.95	1	5
2	0.9	1	3
3	0.8	1	1
4	0.75	0.8	0.5
5	0.75	0.8	0.5
6	0.75	0.8	0.3

Table 2. Communication node attributes

Communication node	Communication capability	Combat information transmission capability	Communication time lag (min)
7	0.95	1	1
8	0.9	1	0.8
9	0.8	1	0.6
10	0.7	0.8	0.4
11	0.6	0.8	0.2
12	0.6	0.8	0.1

Table 3. Decision node attributes

Decision node	Command capability	Command information transmission capability	Command time lag (min)
13	1	1	10
14	0.9	1	8
15	0.8	1	6
16	0.7	0.8	5
17	0.6	0.8	4
18	0.5	0.8	3

Table 4. Kill node attributes

Kill node	Kill ability	Information receiving ability	Kill time lag (min)
19	0.95	1	6
20	0.9	1	5
21	0.8	1	4
22	0.7	0.8	3
23	0.6	0.8	2
24	0.6	0.8	1

Table 5. Target node attributes

Target node	Importance weight
25	0.2
26	0.3
27	0.4
28	0.1

Table 6. Quantity of each relationship edge

Category	Quantity	Category	Quantity	Category	Quantity
P1	7	P4	6	P7	5
P2	7	P5	6	P8	5
P3	7	P6	6	P9	5
γ	1				

5.2 *Experimental results and analysis*

According to the data given in Tables 1-6, use Pyhton NetworkX to generate a combat system network with the blue square as the research object, as shown in Figure 1.

The calculation steps of the key node method are identified according to the performance betweenness and evaluation criteria, and the experimental results are obtained through simulation as shown in Table 7.

Table 7. EBC, Q_i and node sorting

Q_i	Sort	E_i	Sort	E_i^2	Sort	E_i^3	Sort
0.66	12	5.19	16	1.05	12	0.49	12
0.57	6	4.77	12	0.97	16	0.47	16
0.56	16	4.46	3	0.95	7	0.47	7
0.55	7	4.42	7	0.91	13	0.47	13
0.50	13	4.39	13	0.90	3	0.46	3
0.49	3	4.06	15	0.84	8	0.45	8
0.44	15	3.86	8	0.82	15	0.44	15
0.42	8	3.46	6	0.80	6	0.40	6
0.35	21	3.02	21	0.70	21	0.39	10
0.25	10	3.02	10	0.62	10	0.36	21
0.19	9	2.31	4	0.51	9	0.32	11
0.16	11	2.26	11	0.47	11	0.31	9
0.15	4	2.15	9	0.44	4	0.30	14
0.14	14	2.13	17	0.42	14	0.30	4
0.14	17	2.03	14	0.41	17	0.29	17
0.13	23	1.43	1	0.30	23	0.20	1
0.08	1	1.23	24	0.26	1	0.19	23
0.06	24	1.00	23	0.18	18	0.16	18
0.05	22	0.93	22	0.17	24	0.13	24
0.05	18	0.87	18	0.09	22	0.06	22
0.02	5	0.50	5	0.05	5	0.04	5
0.00	2	0.00	2	0.00	2	0.00	2
0.00	19	0.00	19	0.00	19	0.00	19
0.00	20	0.00	20	0.00	20	0.00	20

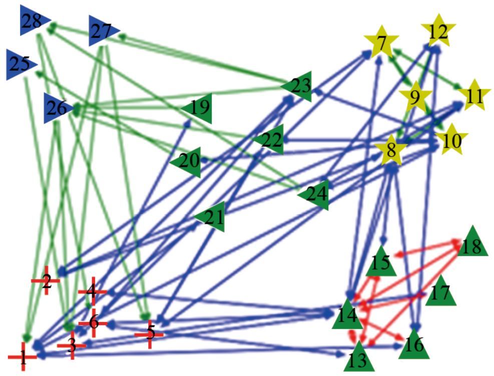

Figure 1. Combat system network

Observe Table 7, three efficiency betweenness calculation methods are used to identify the key nodes of the combat system. The most critical nodes identified by the second method and the third method are the same as the most critical nodes obtained by the system contribution rate, indicating that the second method and the third method have good recognition effect.

By counting the running time of the code, the accuracy and time consumption of various methods are calculated by using Equations (13) and (14), and the experimental results are shown in Table 8.

Table 8. Identification of key nodes in Q_i and EBC method

Method	τ	T (seconds)
Q_i	1	62
E_i^1	0.34	8.8
E_i^2	0.67	3
E_i^3	0.17	5.4

It can be seen from Table 8 that the method based on the contribution rate of the combat system is used to identify the key node T, which takes the longest time. In this paper, among the three calculation methods of the effectiveness betweenness, the Kendall coefficient of the key node ranking result calculated by the second method is the largest, and the time T is relatively short. In summary, the second method for calculating the effectiveness betweenness to identify the key node is the best.

5.3 *Comparative analysis*

In order to test the superiority of the key node identification algorithm based on EBC proposed in this paper, the key node identification method based on Degree (D), Betweenness Centrality (BC), Clustering Coefficient (CC), close Centrality (CL), Eigenvector Centrality (EC), Pagerank (PR) [19], kKWCI [20] is compared, obtain the ranking results of key nodes identified by various methods, and the experimental results were obtained as shown in Table 9.

Table 9. Ranking of key nodes in various method

Q_i sort	E_i^2 sort	DE sort	BC sort	CC sort	CL sort	EC sort	PR sort
12	12	10	10	2	10	10	10
6	16	5	9	13	5	5	15
16	7	9	15	11	15	15	17
7	13	15	17	20	9	9	12
13	3	11	24	21	17	20	5
3	8	12	1	5	12	11	9
15	15	17	6	7	1	14	1
8	6	1	5	14	14	17	11
21	21	6	12	18	6	6	3
10	10	20	7	10	20	12	13
9	9	7	11	15	3	21	18
11	11	13	20	6	11	7	20
4	4	14	4	24	7	13	14
14	14	18	21	1	24	18	6
17	17	3	3	19	13	2	7
23	23	4	14	3	21	16	16
1	1	21	18	4	4	1	4
24	18	24	19	8	18	3	21
22	24	16	2	9	2	24	2
18	22	19	13	12	16	4	19
5	5	2	16	16	8	8	24
2	2	8	23	17	19	19	8
19	19	22	8	22	22	22	22
20	20	23	22	23	23	23	23

By counting the running time of the code, the accuracy and time consumption of various methods are calculated by using Equations (13) and (14), and the experimental results of various methods are shown in Figure 2.

According to the analysis of the experimental results in Figure 2, the key node identification method based on the performance betweenness proposed in this study shows significant advantages compared with the traditional method, mainly reflected in two aspects:

1. The recognition accuracy is improved. Compared with the traditional method based on network structure parameters, this method increases the recognition accuracy to 67%. This improvement is derived from the modeling of network heterogeneity characteristics of the combat system. The traditional method only considers topological structure characteristics (such as degree centrality, betweenness centrality, etc.), while ignoring the differences in node effectiveness attributes. This method couples the node combat effectiveness attributes with network topology characteristics by introducing the performance betweenness index, so as to more accurately reflect the criticality of nodes in the actual combat system.

2. Computational efficiency optimization. Compared with the method based on system contribution rate, the calculation time of this method is reduced by 347%. Under the premise of maintaining a high recognition accuracy ($67 \pm 2.1\%$), the average time of a single recognition is only 3 seconds, which is significantly improved compared with

the benchmark method (62 seconds). This "precision-efficiency" collaborative optimization makes it particularly suitable for real-time analysis requirements of large-scale dynamic combat networks.

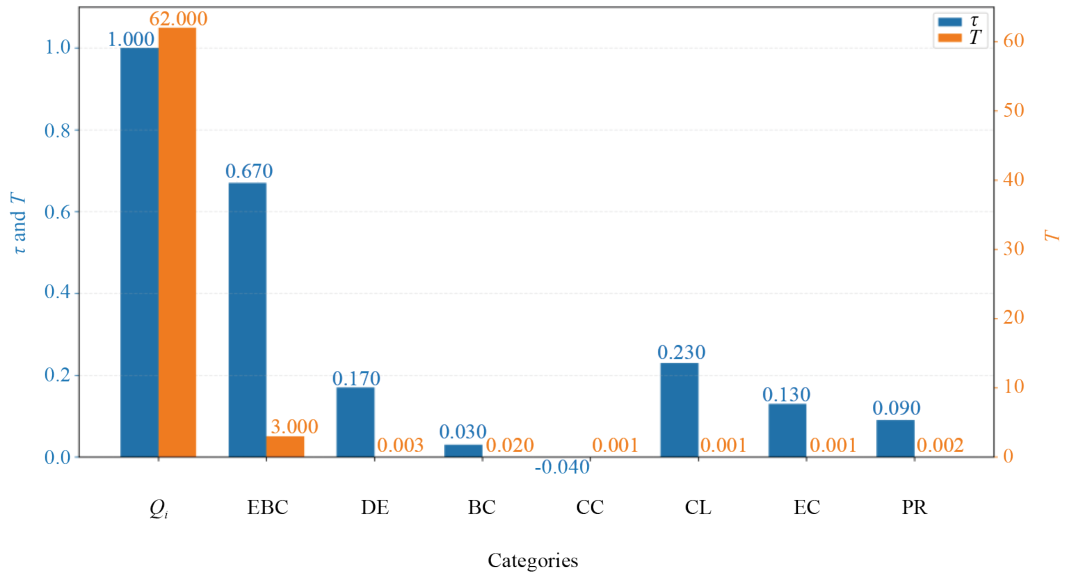

Figure 2. Accuracy of identifying key nodes using various methods

6. Conclusions

In this paper, an innovative algorithm based on performance betweenness is proposed for the identification of key nodes in the combat system. Through theoretical modeling and experimental verification, the following results are achieved:

Problem-solving effectiveness level:

A multi-layer network model integrating Observe, Orient, Decide, Act (OODA) winning mechanism and kill chain efficiency is successfully constructed, which solves the identification bias problem caused by traditional methods ignoring the heterogeneity of combat nodes (such as equipment effectiveness, command relationship, etc.).

The accuracy of the proposed algorithm reaches 67% in the simulation experiment, which is 23.3% higher than that of the traditional structural parameter method (such as degree centrality and betweenness centrality), verifying the feasibility of solving the key node identification problem of the actual combat system.

Theoretical level:

Combining time efficiency (OODA cycle) with network topology (betweenness centrality) provides a new paradigm for modeling complex systems.

Application level:

The efficiency of the algorithm (reducing time consumption by 347%) makes it suitable for battlefield real-time decision support systems.

Future research will focus on collaborative relationship modeling, cascade failure analysis, intelligent optimization algorithms, and military scenario verification to further improve the accuracy, robustness, and practical applicability of key node identification methods, providing theoretical support for system optimization in future intelligent warfare.

Conflict of interest

The authors declare no conflict of interests.

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