Complex Network-Based Quantitative Assessment of Critical Areas of Municipal Power Supply Networks

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Abstract. The power supply network is a matter of urban security and is the foundation for the operation and development of modern cities. As strike capacity escalates, it is critical to find critical areas of the municipal power network. In this study, we construct a comprehensive quantitative value assessment method covering both the site's own value and system value characteristics and integrate site importance and site geographic location information to quantitatively assess critical areas. The framework is realized for quantitative assessment of critical areas of infrastructure networks in a case study of a municipal power network.

Keywords: Complex Networks; Water Supply Network; Critical Areas; Municipal facilities

1 Introduction

The urban critical infrastructure network is the core component of urban planning and construction, which is the energy base to ensure the normal operation of urban functions. In the study of infrastructure networks, the topological relationships in infrastructure networks are usually extracted by simplifying stations to nodes and transmission pipelines to edges. However, in practical engineering, it is difficult to determine the importance of each node by topological relationship alone, which makes the selection of critical areas of urban infrastructure networks difficult.

Patterson and Apostolakis et al. divided the infrastructure within a university into hexagons with a radius of 7m and simultaneously removed the nodes and edges within the area, thus evaluating the critical parts of the system [1]. Johansson and Hassel et al. determined the key areas by dividing the area into 5 × 5 km² and 2.5 × 5 km² squares, and later by analysis [2]. And indeed, the shape of the area has an impact on the choice of critical areas. Min Ouyang et al. consider local space attacks while removing nodes and edges in a region and design algorithms to search for key regions [3]. Pavlik, L analyzes predefined organizational parameters in different cyber threat scenarios and proposes an analysis of the impact on selected threats when the cyber risk insurance domain is known [4]. However, it only considers the critical areas and has not yet considered how the defense resources are allocated, and the area radius has a greater impact on the selection of critical areas. In fact, the determination of infrastructure critical areas is the basis for further protection work.

The value of different sites in an infrastructure network can be measured in terms of both the site's own value and the site's system value. The value of the site itself refers to the value of the site's own equipment and its functions; the value of the system is mainly the important role assumed by the site in the network system. In urban comprehensive disaster prevention planning and people's air defense engineering planning, according to the city's own construction development, it is necessary to arrange various emergency repair teams in key areas, so as to carry out emergency repair of damaged infrastructure in time after the disaster and guarantee the normal operation of urban functions. However, there is no systematic and quantitative assessment method for the screening of critical areas of urban infrastructure. The selection of sites for emergency

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repair works under limited scale conditions has become an urgent problem for decision makers.

Therefore, this study proposes to integrate hierarchical analysis with complex network theory efficiency to evaluate urban critical infrastructure network sites for the above-mentioned problem of quantitative screening of urban infrastructure network critical areas. On this basis, the service radius limitation of engineering rescue and repair specialized teams during wartime and disaster is considered. Therefore, this study is based on quantitative search of sites in the whole area based on their service radius to screen out the key areas of urban power supply network and determine the location of protective emergency repair resources accordingly so that they can maintain the normal operation of urban power supply to the maximum extent in emergency situations.

2 Municipal Power Supply Network Site Importance Assessment

Municipal power supply network site importance assessment is mainly determined by its own importance and system importance, where its own importance can be assessed by using hierarchical analysis method; system importance can be assessed by using complex network theory connectivity.

2.1 Self-Importance Assessment

The study proposes to use AHP to quantitatively assess the importance of municipal power supply network sites themselves. AHP is a combined qualitative and quantitative, systematic and hierarchical multi-objective hierarchical weighting decision analysis method. The method is universal and valid in dealing with complex decision problems, so it is valuable for assessing its own importance.

The determination of weights by hierarchical analysis first requires the construction of a judgment matrix, and the determination of weights is only qualitative and usually not easy to obtain consensus. Therefore, the hierarchical analysis method uses the consistent matrix method to compare the different elements separately in two, and uses relative scales to minimize the difficulty of comparing factors of different nature. Thus, the accuracy is improved. Let aij be the result of importance comparison between element i and element j, and construct a judgment matrix according to the result of two-two comparison. aij can be expressed by Equation 1.

$$a_{ij} = \frac{1}{a_{ji}} \tag{1}$$

The scaling method for determining the elements of the matrix a_{ij} is shown in Table 1.

Table 1. Proportional scale.

Factor *i* vs. *j*	Equally important	Slightly important	Stronger important	Intensely important	Extremely important
Quantified values	1	3	5	7	9

The judgment matrix constructed according to the above table is related to the random consistency index *RI*, and the matrix meshing number is proportional to the possibility of random deviation of consistency, that is, the larger the matrix order is, the greater the possibility of random deviation of consistency. When the judgment matrix meshing is greater than 2, the consistency test is required. The consistency index *CI* is shown in Equation 2.

$$CI = \frac{\lambda - n}{n - 1} \tag{2}$$

where *n* is the order of the judgment matrix and is the eigenvalue of the judgment matrix. When *CI* tends to 0 or equal to 0, the more obvious the consistency is, and vice versa the more obvious the inconsistency appears. To quantify the *CI*, the stochastic consistency index *RI* is introduced as shown in Equation 3

$$RI = \frac{CI_1 + CI_2 + \ldots + CI_n}{n} \tag{3}$$

In the formula, the random consistency index *RI* is related to the order of the judgment matrix, in general, the larger the order of the matrix, the greater the possibility of consistent random deviation, and the relationship between the random consistency index *RI* and the corresponding order of the judgment matrix is shown in Table 2.

Table 2. Average Random Consistency Index RI Standard.

Matrix Order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Considering the impact of the deviation from consistency by the attendant causes, the test coefficient *CR* is also compared with the *CI* and the consistency index *RI* when testing whether the judgment matrix has satisfactory consistency, as shown in Equation 4.

$$CR = \frac{CI}{RI} \tag{4}$$

If CR < 0.1, the judgment matrix will be considered to satisfy the consistency test.

2.2 System Importance Assessment

The importance of a site in the network can be assessed using system importance, which is the impact of an individual site on the networks as a whole. In existing studies, parameters such as connectivity [5-7], connection density [7- 8], average node degree [8], and average meshing are commonly used to measure the performance of network structures. This study focuses on quantitatively measuring the connectivity of all nodes in the network, so network connectivity is used to measure the network.

Assessing network connectivity based on complex network theory network efficiency. The sum of the inverse of the average shortest distance between any two point pairs in the infrastructure network, the network connectivity formula, is shown in Equation 5.

$$\varepsilon = \frac{2}{N(N-1)} \sum_{i>j} \frac{1}{d_{ij}} \tag{5}$$

where d_{ij} is the shortest path between i and j in the infrastructure topology network and N is the number of sites. In order to reflect the connectivity efficiency of different infrastructure networks, the network efficiency ε can be used to evaluate the network, and the higher the value, the higher the network connectivity efficiency.

Based on this, this paper proposes the rate of change of infrastructure network connectivity as a measure of system value. The connectivity efficiency of the infrastructure network tends to change when certain sites are disrupted, and the amount of change in connectivity efficiency is shown in Equation 6.

$$\Delta\varepsilon_i = \varepsilon_i - \varepsilon_0 \tag{6}$$

where ε_i denotes the network connectivity after site disruption and ε_0 denotes the network connectivity in the initial state. When a node suffers damage, the greater the amount of change in its connectivity efficiency, the higher the value of the node system and the more important it is in the network.

The system value of each site is normalized to determine the system value of each site P_{Si} can be determined by Equation 7.

$$P_{Si} = \frac{\Delta\varepsilon_i}{\sum_{i=1}^{N} \Delta\varepsilon_i} \tag{7}$$

where $\Delta\varepsilon i$ denotes the change in network connectivity before and after site disruption in the infrastructure network, and N is the number of sites.

2.3 Comprehensive Value Assessment

Based on the importance *M*(*i*) of each site of the urban infrastructure network itself and the system importance *S*(*i*), the combined importance *P*(*i*) of each site in this paper can be determined by Equation 8.

$$P_{(i)} = \omega M_{(i)} + (1-\omega) S_{(i)} \tag{8}$$

where *w* is the weight ratio of own value to system value. In fact, *w* can be solved according to hierarchical analysis [9-10], but in this study, *w*=0.5 can still effectively analyze the critical area.

3 Quantitative Analysis Assessment Framework for Key Regions

In order to consider both the self-importance and system importance of sites, this paper constructs a quantitative screening research framework for critical areas of urban critical infrastructure networks based on hierarchical analysis and complex network theory efficiency methods, as shown in Figure 1. In this evaluation framework, in order to accurately reflect the comprehensive importance of different sites, this paper constructs a two-by-two comparison matrix between different sites through AHP to determine the own importance of each site; at the same time, the system importance of each site in the network is measured by using complex network theory efficiency, so that the target system importance can be fully reflected. On the basis of this, a program was designed to search and rank the combinations of sites within the specified area radius based on the regular service radius of the emergency repair team and on the basis of a circle. Finally, a research model for quantitative calculation of critical areas of urban infrastructure networks is established, and quantitative fusion assessment of critical areas of urban critical infrastructure networks is realized by integrating the importance of different sites themselves and the system importance.

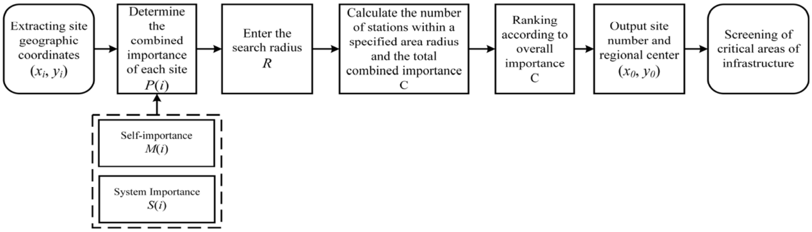

Fig. 1. Quantitative Assessment Framework for Critical Areas of Infrastructure Networks.

According to the research framework shown in Figure 1, the quantitative screening of critical areas of urban infrastructure networks is divided into the following steps after considering the importance of different sites themselves and the importance of the system.

Step 1: Extract the geographic coordinates (x_i, y_i) of the different sites. Based on the geographic junction map of the urban infrastructure network, the geographical locations of different stations are determined. The location relationship between different sites is clarified to provide a basis for searching the number of sites under the specified service radius R.

Step 2: Specify the importance of different sites $M(i)$. Based on the hierarchical analysis method, we construct a comparison matrix to evaluate the importance of different sites and quantitatively determine the value of different sites.

Step 3: Calculate the system importance of different sites $S(i)$. Based on the theoretical efficiency of complex networks, we calculate the network efficiency of different sites in the topology and quantitatively determine the system importance of different sites.

Step 4: Calculate the comprehensive importance of each site $P(i)$. Based on the interrelationship between the importance of each site and the importance of the system, the weighted composite importance of the urban infrastructure network is calculated.

Step 5: Solve the total composite importance C of the optimal combination of sites within the specified area radius. And calculate the total composite importance C of each station within the regional radius, and rank the total composite importance in the order of highest to lowest.

Step 6: Screening critical areas of urban infrastructure network. Based on the total comprehensive importance ranking, the center of the area with higher total comprehensive importance ranking is used as the center of the circle to determine the radius of the critical area, and the critical area is screened with the actual situation.

4 Case Study

This study takes a city electric power supply network as an example, as shown in Figure 2. The key areas are screened according to the research framework to provide theoretical guidance for the arrangement of the city's specialized electric power rescue and repair teams.

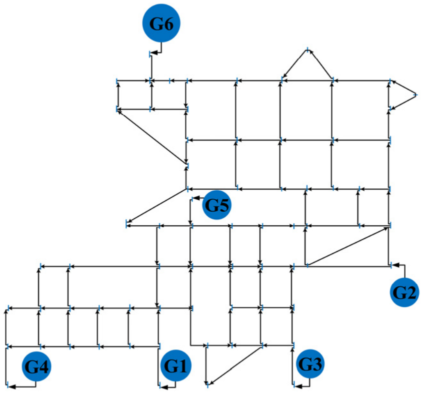

Fig. 2. City power supply network chart.

4.1 Parameters of Each Key Substation Equipment

The urban power supply network in this case mainly consists of power stations, 550kV substations, 220kV substations and 110kV substations. The main consideration is that these facilities are the backbone of the city's power supply network to ensure the effective operation of the backbone part to achieve the protection target under emergency situation. The function of the 550kV substation is to downscale power from the city's peripheral high-voltage transmission network to serve the city. Therefore, when a city grid is the object of study, after establishing the city grid boundary, the 550 kV substation can be functionally equivalent to a power site (power station). The geographic grid junction of a case city is shown in Figure 3.

As a simplified count, there are six equivalent sources in the city's power grid, including four power plants and two 550 kV substations in the city. The specific parameters of each are shown in Table 3. In fact, for a 550kV substation, the high-voltage transmission network is usually looped to ensure the normal operation of the backbone network in case of damage to a single site. However, for a given city, a small city can contain up to two 550kV substations, which are key hubs for the city's lifeline to external energy sources.

Table 3. List of Equivalent Power Supply Sites.

Number	Site	Variable ratio	Capacity Composition	Power (MVA)
G2	transformer substation	500/220/35KV	3*750	2250
G3	transformer substation	500/220/35KV	3*750	2250
G4	transformer substation	500/220/35KV	2*1000	2000
G6	transformer substation	500/220/35KV	2*1000	2000
G5	Power station	--	--	50
G1	Power station	--	--	30

As can be seen from Table 3, the power generation of the power plants in the city is small, and the city's power grid is mainly introduced by the peripheral power grid through 550kV substations, and the two 550kV substations are responsible for the main task of supplying power to the city, and are also important for ensuring the city's The two 550kV substations are responsible for the main task of supplying power to the city and are also important protection objects to ensure the power supply of the city. Due to the large number of 220 kV substations and 110 kV substations, it will not be repeated here.

5 Results and Discussion

5.1 Assessment of the Importance of the Site Itself

In general, during the construction of the comparison matrix, the expert scoring method is needed to score the comparison between the two comparisons, and then a consistency test is performed. However, in a power network, since the maximum load of a 110kV substation is known, a two-by-two comparison matrix can be constructed directly from the maximum load, since the maximum load number usually also directly reflects the role of the substation in the network. Similarly, the capacity of 220 kV substations and 550kV substations is known, so a two-by-two comparison matrix can be constructed accordingly. Since the relative two-comparison data are quantitatively determined, the constructed matrix is directly consistent, and compared to the expert scoring method, it does not require a consistency test to solve for the respective weights.

For the urban grid, the 550 kV high-voltage substation, as the highest level energy source, can be equivalently considered as a power source. Therefore, in this case, there are power source C1 (power station and 550 kV high voltage substation), 220 kV substation C2 and 110 kV substation C3. Accordingly, a two-by-two comparison matrix is constructed as follows table 4.

Table 4. Site Comparison Matrix.

C_k	C1	C2	C3
C1	1	3.75	12
C2	0.27	1	3.2
C3	0.08	0.3125	1

The weighting ratio between power station, 220kV substation, and 110kV substation is $[C1, C2, C3]^T = [0.7404, 0.1975, 0.0618]^T$.

The importance of each site is derived by comparing power stations, 220kV substations, and 110kV substations according to their power levels, and combining the values with the above weights, and some of the data are shown in Figure 3 below.

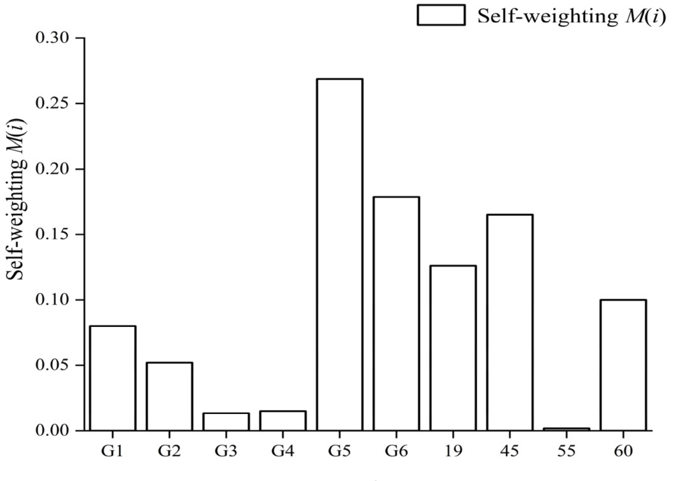

Fig. 3. Importance of own value of some sites of urban power network.

5.2 Site System Importance Assessment

The system value of a site indicates the role that the site assumes in connecting the entire network. The different roles of substations of different levels in the network are considered in the site's own value, while the system value of the site mainly considers the differences in the roles of substations of the same level when they are distributed in different locations in the network. For example, in some special cases, a substation bears the connection hub between the main city and the central city, although the substation voltage level is the same, but its system value is much higher than other sites, becoming the key site in the system protection.

The initial connectivity of the network is calculated according to Equation 5., and on top of that, the connectivity of the new network is calculated by removing each site in the power supply network separately. The system value importance of each site in the network can be calculated from Equations 6. and Equations 7., and the value importance of some sites is shown in Figure 4.

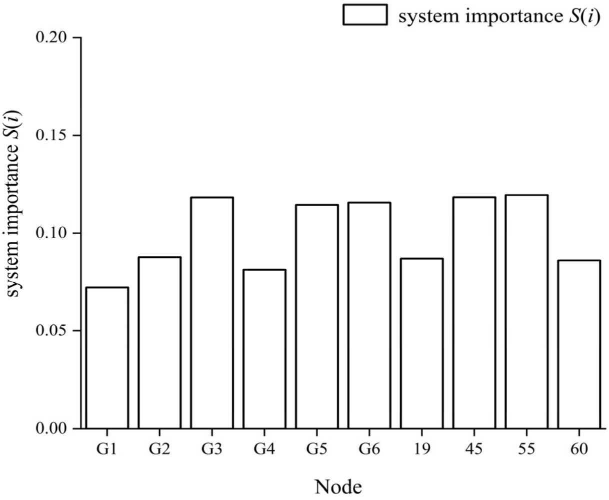

Fig. 4. City grid part of the site system importance.

5.3 City Grid Key Site Assessment

According to Equation 8, the comprehensive weighted value of each site of the network's own value and system value is calculated, and the comprehensive value $P(i)$ importance of each site in the network can be derived, where some of the comprehensive importance is shown in Figure 5. The results of the quantitative analysis determine the importance of each site, clarify the key position of each site in the urban grid, and lay the foundation for the next quantitative search of the key area.

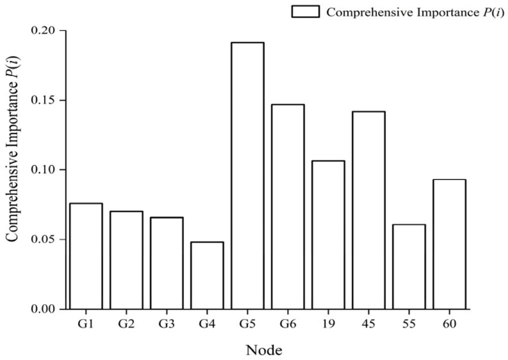

Fig. 5. Comprehensive importance of key sites in urban power networks.

5.4 Critical Area Selection for Urban Grids

Considering the timely concealment needs of human defense repair and rescue professional team in wartime, usually its service radius is about in the range of R=2500m. In the screening process of key areas, there will generally exist several areas with high comprehensive value C adjacent or close to each other, and the most important areas need to be selected from different areas as key emergency repair areas according to decision makers, so as to provide the allocation basis for the optimal arrangement of urban protection resources.

As shown in Figure 6, from each key area in the top 30 of the city grid ranking, one most important area is selected as the core protection area from different areas according to the principle of uniformly dispersed arrangement. In this study, there are five core protection areas, two of which contain power stations, fully reflecting the role of power stations and advanced substations in the urban grid.

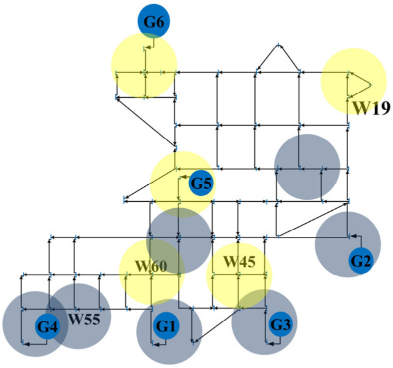

Fig. 6. City power network key protection area.

The relative importance of each key protection area is shown in Figure 7, among which target area 1 and target area 2 both contain 500 kV substations, and their comprehensive value is higher than the rest of the areas.

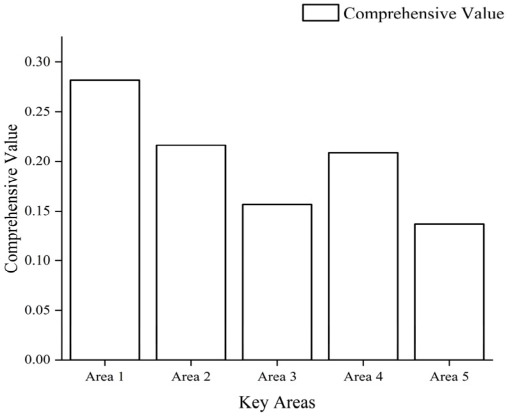

Fig. 7. Key protection area importance degree.

Under the background of limited protection resources, the protection resources are arranged in the above five core areas to ensure the normal operation of the city grid and maintain the orderly operation of the city's lifeline to the maximum extent.

6 Conclusion

This study aims to quantitatively screen the key areas of urban critical infrastructure networks, and the importance of urban infrastructure network sites can be measured in terms of both their own importance and system importance. Therefore, this chapter adopts the hierarchical analysis method to quantitatively assess the own value of each site and the system value of each site using the amount of change in network connectivity in complex network theory, and then integrates the own value and system value of each site to determine the comprehensive value of each site in the urban grid. On this basis, by searching the key areas of the city grid, we finally determine the urban core area of the city grid protection.

In the case study of a city power network, we first quantitatively analyze the integrated value of each site in the city power supply network, which is determined by both its own value and the system value. Then, we quantitatively searched the key areas of the urban power network under the specified radius R=2500m. The results show that power stations and high-grade substations play a crucial role in the selection of critical areas of the urban power network. Secondly, the overall value of the 220 kV substation network in the power network is higher than that of the 110 kV substation, and the relative geographical location among the substations also directly affects the determination of critical areas.

Through quantitative screening of the core areas of urban power grids, the core areas of urban power grid protection are determined, which directly guide the location arrangement of wartime electric power rescue and repair professional teams. The foundation is laid for the subsequent allocation of urban grid protection resources in the context of limited protection resources. The next step of this study will be to conduct more in-depth research on the reasonable allocation of defense resource allocation to multiple key areas of the urban grid and urban grid resilience.

Conflicts of Interest

The authors declare no conflict of interest.

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