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# Asymmetric evolutionary game analysis of emergency cooperative social networks for magnitude emergencies: Evidence from the Beijing-Tianjin-Hebei region in China

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Emergency cooperative social networks (ECSNs) play a very important role in emergency management for magnitude emergencies in China recently. Based on the data set of cooperative fight against COVID-19 of the Beijing-Tianjin-Hebei region in China, using social network analysis (SNA) and asymmetric evolutionary game model, this study finds that the asymmetry between regions is comprehensively determined by resource endowment, administrative level, geographical distance, regional vulnerability, political pressure and other factors; vertical control is still the main operating mechanism of ECSNs; network derivation is caused by the superposition of multiple factors, of which political factors are very important, and asymmetry may become an obstacle.

KEYWORDS

**emergency cooperative social networks (ECSNs), magnitude emergencies, game theory, asymmetry, social network analysis (SNA)**

## 1 Introduction

In the post-crisis era, magnitude emergencies occur frequently, involving multiple fields and spreading to a wide range. They have a large degree of influence and have complex characteristics, such as mass occurrence, diversity, and coupling of derivative secondary events. Therefore, it requires cross-regional emergency cooperation [1–3]. With the unified goal of managing magnitude emergencies, social actors at all levels in the region reach emergency cooperation relations through joint meetings, policy releases, exercises, resource assistance, and business guidance, and form the emergency cooperative social networks (ECSNs). The ECSNs are an effective organizational form to address magnitude emergencies, and have the function of coordinating emergency response, integrating emergency resources, and improving emergency response effectiveness. This is crucial to the improvement and guarantee of emergency management capacity of countries all around the world. In recent years, literature on the ECSNs for magnitude emergencies has emerged, focusing mainly on the causes, structure, and effects of the networks, and focusing less on the operation and formation mechanisms of the networks. Therefore, based on the detailed analysis of the ECSNs, this paper analyzes their operation and formation mechanisms. This research answers three questions: 1) What are the characteristics of the ECSNs for magnitude emergencies? 2) What is the cooperation mechanism of the ECSNs for magnitude emergencies? 3) What is the mechanism of cooperative strategy selection of each subject in the networks? Based on the above questions, this paper takes the Beijing-Tianjin-Hebei (B-T-H) region in China as a sample and analyzes the emergency cooperation practices for COVID-19 from the following aspects: 1) The construction and analysis of the ECSNs for magnitude emergencies. Crawler and Social Network Analysis are used to search a large number of samples and obtain relevant data to build the ECSNs. Through the analysis of overall network characteristics, individual node attributes, and cohesive subgroup, the subject composition, connection, and operation mode of the ECSNs are deconstructed, and the cooperation mechanism is analyzed. 2) The asymmetric evolutionary game analysis of the ECSNs for magnitude emergencies. Emergency cooperation is accompanied by game behavior, and the subject strategy choice and its rules reflect the generation mechanism of the ECSNs. Asymmetry is a universal phenomenon that exists widely among the subjects in the networks. Therefore, this paper conducts asymmetric evolutionary game analysis on the ECSNs for magnitude emergencies to explore the generation mechanism and evolutionary influencing factors of the ECSNs.

The contributions of this study are significant both in theory and practice. First of all, different from the previous researches on the network structure and function at the macro level, this study makes a detailed analysis of the ECSNs structure in specific sample areas by comprehensively using the SNA, asymmetric dynamic evolutionary game and SD simulation method. On this basis, it analyzes the influencing factors, operation mechanism and generation mechanism, further focuses on the research perspective, and enriches and expands the existing researches from the meso-level. Second, the empirical analysis of the ECSNs in the B-T-H region of China can provide the world with Chinese wisdom and experience, explore the world's emergency cooperation problems with China as the incision, and provide experience for countries to improve the ECSNs and increase the quality of emergency cooperation.

The paper is arranged as follows: The second chapter summarizes the existing researches and puts forward relevant hypotheses based on the existing literatures. The third chapter introduce methods, samples and data. The fourth chapter introduces the results of social network analysis. The fifth chapter introduces the results of asymmetric evolutionary game analysis and SD simulation. The sixth chapter provides the conclusions of the study.

## 2 Literature review

The ECSNs is a dynamic structure formed by formal and informal cooperation between organizations of different types and scales in the context of crisis management [4, 5] having a positive role in promoting the sharing of information, financial resources and human capital, which is conducive to the improvement of emergency management efficiency [6].

The subjects in the ECSNs gather for common goals and are mutual stakeholders, and the asymmetry among stakeholders is a common problem in cooperative networks [7]. Traditional theories suggest that asymmetries of power are not conducive to the establishment of cooperative relationships [8]. This asymmetry is manifested in resource endowment, administrative level, geographical proximity, degree of disaster impact and other aspects [9–15]. If there is a serious asymmetry between network actors, the stronger party will take the initiative, and occupy the central position of the network and control network resources, while the weaker party will find it is difficult to participate effectively, leading to a crisis of confidence or void contract [6]. Moreover, the actors in the ECSNs are interconnected, which makes them vulnerable to each other's strategic behaviors [16]. In asymmetric power relations, the stronger organization may hijack the weaker organization for its own purposes [17], so that the weaker party will lose interest in participating in cooperation. Therefore, it is assumed that inter-agent asymmetry is not conducive to the formation and close operation of ECSN.

The ECSNs contribute to information transmission because of its multi-directional network connections, and its flexible and diverse network structure promotes the improvement of emergency efficiency. First of all, vertical control is the continuation of the bureaucracy structure under the conventional situation, and this mechanism has the rationality of system logic. From the perspective of institution, as part of the national administrative organization, local governments at all levels are accountable to higher levels of government. Tasks assigned by superiors are an important part of local government responsibilities. From the perspective of intrinsic motivation, obedience to leaders helps local governments maintain an edge in peer competition. In addition, as a representative of the central authority, the participating superior governments can reduce transaction costs and cooperation risks [18]. Therefore, vertical control by higher levels of governments helps to build trust and respect among local government entities at all levels and foster cooperative networks [19]. Second, in the theoretical framework proposed by Ansell and Gash (2007) [6], they point out that when the distribution of power is asymmetric or the motivation to participate is weak, the success of cooperative governance requires leadership control. This proposition implies that vertical control is critical to social networks. Especially in China, the involvement of national/provincial governments will lead to more authoritative agreements [20]. Therefore, vertical control is assumed to be the dominant mechanism for the ECSNs, with other forms of cooperation as auxiliary.

Many studies have explored the causes of social networks. Based on previous studies, the essence of the formation of ECSNs can be summarized as follows: multi subjects form a cooperative network by establishing cooperative relations based on common emergency objectives (insert references), the causes of the network can be decomposed into the stimulation of environmental factors and the formation of emergency cooperative relations [21]. Some scholars have pointed out that environmental factors are the initial conditions for triggering social networks, especially the emergency management scenarios that give birth to ECSNs. For example, Bryson, Crosby, and stone (2006) propose a framework for understanding cross sector collaborations [22]. Some of the initial conditions for cooperation are environmental factors, such as turbulence and complexity. Head and Alford (2013) pointed out that major emergencies go beyond administrative levels and policy areas, and are complex, fuzzy and uncertain, forcing the generation of cooperative networks to deal with emergencies [23]. At the same time, the formation of emergency cooperation is caused by many factors. Social networks promote better performance through collective action rather than through individual organizational efforts [24–27]. And the development of the Internet, World Wide Web and smart mobile devices has also provided technical support for ECSNs and promoted the development process of online networks [28]. Under the Logic of Collective Action framework, authorities choose whether to participate in different mechanisms based on transaction costs and cooperation risks [29]. These factors are often intertwined, with many working together to build partnerships. Similarly, Emerson, Nabatchi, and Balogh (2012) suggested that cooperation is unlikely to continue without a combination of at least one or more other drivers (indirect incentives, interdependence, and/or uncertainty), which implicitly pointed to the generality of network generation [30]. It is worth noting that among many factors, political factor -- institutional pressure cannot be ignored. Wen Xuemei and Suo Liming (2020) pointed out that regional emergency cooperation becomes closer under political pressure [31]. In many centralized and federal systems, the central/federal governments use institutional pressure -- accountability mechanisms to enforce the will of the higher authorities at all levels below the state [32]. In China, local governance has similarities and differences with western countries [33, 34]. Considering the particularity of emergency situation, we assume that the ECSNs are caused by many factors, among which political factors have a greater impact.

Combined with the logic of network structure response operation mechanism, this paper chooses SNA to analyze the operation mechanism of ECSNs. Referring to the Logic of Collective Action framework to explain the formation mechanism of the social networks, considering the widespread existence of asymmetry between the actors in networks, the formation mechanism of the ECSNs is analyzed by using asymmetric evolutionary game combined with SD simulation analysis.

# 3 Methods, simples and data

## 3.1 Methods

### 3.1.1 Social network analysis (SNA)

SNA is an important method to study the interaction between action objects and the overall network structure. It provides a feasible tool for examining the structure and operation mode of a social system by visualizing the interaction between actors in the networks and evaluating them through a series of indicators [35, 36]. This paper analyzes the ECSNs for COVID-19 in the B-T-H region from overall network structure, individual network structure, and cohesive subgroup analysis.

#### 3.1.1.1 Overall network structure

The ECSNs structure of the overall network is analyzed by measuring the density of the overall network. Density refers to the ratio of the actual number of connections in the network to the maximum possible number of connections, thereby reflecting the density of the ECSNs, and the value is between 0 and 1. The higher the network density, the closer the connection between the subjects.

#### 3.1.1.2 Individual network structure

The indicators of individual network structure include degree centrality, betweenness centrality, and closeness centrality [37]. The network position of each subject in the ECSNs can be explored by calculating them.

Degree centrality. Degree centrality is the sum of points connected directly to other points. The central position and cooperation enthusiasm of each region in the ECSNs can be found by degree centrality analysis. Degree centrality is divided into absolute degree centrality ($C_D(n_i)$) and relative degree centrality ($C'_D(n_i)$). Absolute degree centrality refers to the number of other points directly connected with the point. Relative degree centrality is the ratio of the absolute point centrality to the maximum possible degree of a point in the graph. The calculation formulas are as follows:

$$\boldsymbol{C_D(n_i) = d(n_i) = x_{i+} = \sum_j x_{ij} = \sum_j x_{ji}} \tag{1}$$

$$C_D^{'}(n_i) = d(n_i)\big/g - 1 \tag{2}$$

Considering the directivity of connection, the degree of centrality can be divided into out-centrality and in-centrality. Among them, out-degree centrality is the sum of a point pointing to other points, showing the degree of a region's concern on other regions. In-degree centrality is the sum of a point pointed by other points, showing the attention of a region and measuring its prominence. Its calculation formula is as follows:

$$C_D(v_i) = \sum\nolimits_{i=1, i \neq j}^{n} d_i^{in} \tag{3}$$

$$C_D(v_i) = \sum\nolimits_{i=1, i \neq j}^{n} d_i^{out} \tag{4}$$

Betweenness centrality. Betweenness centrality is the number of shortest paths to a point. It represents the extent to which one actor stands between the other two actors, namely, the ability to build bridges for other actors and the degree to which each region has control over emergency resources can be determined through the betweenness centrality analysis. Betweenness centrality is divided into absolute betweenness centrality and relative betweenness centrality and calculated by the ratio of geodesics at any other two points and the number of geodesics passing through that point (geodesics indicate the shortest distance between two points). The calculation formulas are as follows:

$$C_B(n_i) = \sum\nolimits_{j<k} g_{jk}(n_i)\big/g_{jk} \tag{5}$$

$$C_B^{'}(n_i) = C_B(n_i)\big/\left[(g-1)(g-2)/2\right] \tag{6}$$

where$g_{jk}$represents the number of the shortest path connecting two actors, and $g_{jk}(n_i)$represents the number of the shortest path connecting actors $j$and $k$including actor $i$.

Closeness centrality. Closeness centrality is the average length of the shortest path of each node to other nodes, and the greater the closeness centrality's value, the more it indicates that the point is not the core point of the network. The location of each region in the ECSNs can be determined by the closeness centrality analysis. The degree of closeness centrality is divided into absolute closeness centrality$[C_C(n_i)]$ and relative closeness centrality $[C_C^{'}(n_i)]$. The calculation method is to sum the distance of geodesic between the point and all other points and then derivative. The calculation formulas are as follows:

$$C_C(n_i) = \left[\sum\nolimits_{j=1}^{g} d\left(n_i, n_j\right)\right]^{-1} \tag{7}$$

$$C_C^{'}(n_i) = \frac{g-1}{\sum_{j=1}^{g} d\left(n_i, n_j\right)} = (g-1)C_C(n_i) \tag{8}$$

#### 3.1.1.3 Cohesive subgroup

A cohesive subgroup is a subset of actors in which there are relatively strong, direct, close, or positive relationships among the actors. The cohesive subgroup analysis can explore the subgroups in the network and their closeness, and refine the understanding of the structure and operation mode of the ECSNs. In this paper, the cohesive subgroup analysis of the ECSNs is carried out using clique and image matrix analyses.

Clique. The clique is a subset of actors whose relationships within the clique are closer than those outside the cliques. Clique analysis can explore the cliques and their components in the ECSNs. The calculation needs to reduce the dimension of the data "binarization" processing, the number greater than the critical value "0" is re-coded as "1", otherwise it is "0" (calculation Eq. 9). On this basis, the clique analysis in UCINET is used for clustering.

$$x_{ij}^{'} = \begin{cases} 1 & if\ x_{ij} > 0 \\ 0 & if\ x_{ij} = 0 \end{cases} \tag{9}$$

Image matrix. Image matrix analysis is a method to describe block type from the perspective of the overall network. The intimacy between subgroups can be obtained by image matrix analysis. The method of the a-density index was used to obtain the image matrix: the intimacy between each subgroup was compared with the overall network intimacy, and the value greater than the overall network intimacy (a) was recoded as "1", and vice versa as "0" to obtain the intimacy analysis table between each group. The calculation formula is as follows:

$$b_{klr} = \begin{cases} 0 & if\ \Delta_{klr} < \alpha \\ 1 & if\ \Delta_{klr} \geq \alpha \end{cases} \tag{10}$$

### 3.1.2 Asymmetric evolutionary game

Game theory is a branch of modern mathematics that can be used to study security issues and interactions between decision-makers competing for limited or shared resources [38–41]. Considering the asymmetry between the subjects and the dynamics of the game process, the asymmetric dynamic evolutionary game analyzes the game strategy of the cooperative subjects. In this paper, the asymmetric dynamic evolutionary game is used to deduce the choice of cooperation strategies between the actors in the ECSNs, and then the formation mechanism is analyzed.

First, the mathematical formula of asymmetry is obtained through literature summary and formula derivation. In other words, by introducing the rising Γ distribution exponential function, the multidimensional asymmetric indices are transformed into parameters in the form of a single index (Eq. 11). Normalized the index values to obtain the comprehensive value in each region$(k_i)$ (Eq. 12). The asymmetry between the regions can be defined as $k_i/k_j\,(i, j \in 1, 2, \ldots, n, i \neq j)$, where $\omega_i$represents the weight value of index$P_i$, which can be determined according to the analytic hierarchy process, and$0 < k_1 < 1$, and $\sum_{i=1}^{n} k_i = 1$. In particular, when considering the asymmetry between regions, it is defined as $k/(1-k)$ (Eq. 13).

TABLE 1 Region and abbreviation.

| Region | Abbreviations |
|---|---|
| Beijing | BJ |
| Tianjin | TJ |
| Hebei | HB |
| Shijiazhuang | SJZ |
| Qinhuangdao | QHD |
| Tangshan | TS |
| Baoding | BD |
| Langfang | LF |
| Xingtai | XT |
| Handan | HD |
| Chengde | CD |
| Cangzhou | CZ |
| Hengshui | HS |
| Zhanjiakou | ZJK |
| The State Council | The State Council |
| Joint Prevention and control mechanism | JPCM |
| National health commission | NHS |
| Ministry of science and technology | MOST |
| Ministry of science and technology | the Ministry of Finance |
| Political Bureau of the Central Committee of the CPC | Political Bureau of the Central Committee of the CPC |

$$Pi = \begin{cases} 0 & 0 \leq x_i \leq \delta \\ 1 - e^{-\eta \cdot (x_i - \delta)} & x_i > \delta \end{cases} \tag{11}$$

$$k_i = \frac{\omega_i P_i}{\sum_{i=1}^{n} \omega_i P_i} \tag{12}$$

$$\mu = k/(1-k) \tag{13}$$

Second, on the premise of considering asymmetry, mathematical calculation is conducted on the causes of the strategies selection in each region through the construction and solution of the model. The optimal solution is obtained by constructing Nash equilibrium and the evolutionary phase diagram is drawn to deduce the formation mechanism of the ECSNs.

### 3.1.3 SD simulation

SD simulation refers to the process of simulating an evolutionary game with system dynamics. The results of the asymmetric evolutionary game can be verified through SD simulation analysis, and the effects of the various factors on the evolution of the ECSNs can be analyzed.

First, the value of other variables is kept unchanged, and by adjusting the value of the asymmetry index $k_i$ in each region, the influence of the asymmetry index on the evolution of the ECSNs is analyzed, and the conclusion of the asymmetric evolutionary game is verified.

Second, by adjusting the additional cost indices ($\theta$, $\beta$) of emergency cooperation, the influence of the additional cost on the evolution of the ECSNs was investigated under the two conditions of one party's negative cooperation and both parties' negative cooperation. The influence of economic factors on the evolution of the ECSNs is also explored.

The effects of punishment intensity on the evolution of the ECSNs for magnitude emergencies was explored by adjusting the additional punishment index ($\lambda$) and punishment value ($F$). The influence of political pressure on the ECSNs is explored.

## 3.2 Samples and data

### 3.2.1 Samples

In this paper, the B-T-H region is selected as the research sample of the ECSNs.[1] The reasons are as follows. First, as the most typical urban agglomeration in China, the GDP of the B-T-H region accounts for 44% of the national total, and is a municipality directly under the Central Government and the capital. It has crucial political and economic status. Second, regional cooperation is durable and stable. As early as 2014, the emergency offices of Beijing, Tianjin, and Hebei jointly signed the Emergency Management Cooperation Agreement of Beijing,

1 There are 11 prefecture level cities in Hebei Province, including Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang and Hengshui.

TABLE 2 Text codes and examples related to the emergency cooperation for COVID-19 in the B-T-H region.

| | time | collaborative content | subject | | Scale | level |
|---|---|---|---|---|---|---|
| | | | active | passive | | |
| 1 | 2020.11.28-29 | *Some opinions on strengthening the construction of public health emergency management system in the capital* | Beijing | Tianjin-Hebei | multilateral | province |
| 2 | 2020.02.25 | Video conference on joint epidemic prevention and control in Beijing-Tianjin-Hebei region | B-T-H | | multilateral | province |
| …… | …… | …… | …… | …… | …… | …… |

Tianjin, and Hebei Province and held the joint meeting, providing an institutional guarantee for future emergency cooperation. A working mechanism for the COVID-19 prevention and control was established in 2020, providing stable support for regional cooperation in emergency management. Third, the administrative level and boundary structure of this region are relatively complex, and involves not only the coordination and cooperation between inter-provincial cities but also the vertical coordination at different levels, such as municipalities directly under the Central Government, provinces, sub-provincial cities, and prefecture-level cities. Fourth, the epidemic of COVID-19 at the end of 2019 has brought a huge effect of the world's public health system. China has achieved good results in the fight against the epidemic. Among them, the B-T-H region has achieved remarkable results in emergency cooperation, providing Chinese solutions and wisdom for the world's emergency cooperation.

### 3.2.2 Data

The data searched in this paper were from the official websites of the Central Government, Hebei, Beijing, Tianjin, 11 prefecture-level cities in Hebei (See Table 1), and the websites of the Health Commission. The time limit was from December 2019 to December 2021.

This study uses big data techniques to crawl and download the emergency cooperation information stored on the websites of local governments and the health commission. Because it is impossible to download massive website data directly, it is realized by writing programs. *Python* is a programming language library that provides efficient data structures for simple and effective object-oriented programming. It has been widely used in Web site development, artificial intelligence, spatial statistics, and other applications. In this study, we use the *Python* software to code 28 sets of programming languages, which can be divided into two steps, keywords search and content search to crawl and store data in relevant websites in various regions. On the basis of data collection, data screening and coding are carried out. First, the collected data are cleaned, that is, the retrieval results are manually selected, and the reports that do not involve the sample urban agglomeration, are not related to the research content, and do not belong to the research time range are removed to make them meet the sample conditions. Second, the report is structured by encoding from five dimensions: time, collaboration content, collaboration subject, collaboration scale, and collaboration level. Among them, the dimension of the cooperation subject is divided into positive and negative. If there is a joint document, joint attendance of meetings, long-distance investigation, or cooperation between cities, the host of the meeting, the support party, and the observer party shall be regarded as the positive cooperation subjects, while the others shall be regarded as the negative cooperation subjects. The collaboration level includes provincial, municipal, province-municipal, and central participation (Table 2). The multi-valued directed cooperation matrix is constructed through relational assignment. That is, the relationship is assigned based on structured coding. If the two places jointly send out a document or take joint action, 1 is added to the value of the emergency cooperation between the positive party, while the negative party remains unchanged.

The crawler function of *Python* was used to identify and store the regional emergency cooperation reports within the scope of data search, supplemented by manual screening, and finally, there were 153 reports left.

## 4 Construction and analysis of the ECSNs

### 4.1 ECSNs construction

Using the sorted multi-valued directed relation matrix, Net Draw software was used to draw the ECSNs map of COVID-19 in the B-T-H region (Figure 1). Each region is represented as a point, and the connection between regions is represented as a line. The ECSNs for COVID-19 in the B-T-H region have the following characteristics.

(1) The subjects of emergency cooperation are diverse. The cooperation subjects in the ECSNs involve central,

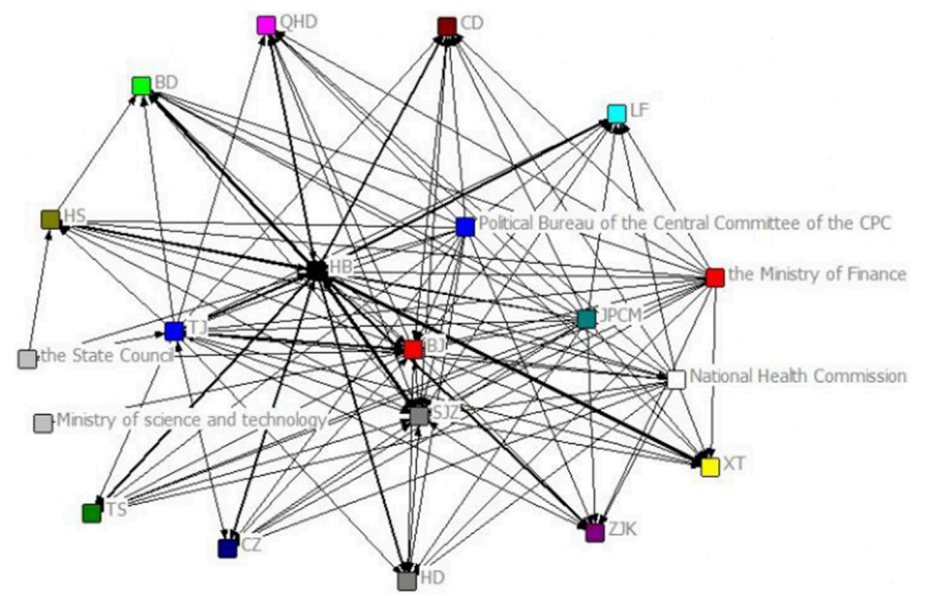


FIGURE 1
map of the ECSNs for COVID-19 in the B-T-H region.

provincial, and municipal levels. The central level includes the State Council, the Political Bureau of the Central Committee of the CPC, the National Health Commission, the Ministry of Science and Technology, the Ministry of Finance, and the State Council's Joint Prevention and Control Mechanism (JPCM) for the COVID-19. At the provincial level, it includes Beijing, Tianjin, and Hebei. The municipal level includes 11 cities in Hebei.

(2) The contacts between emergency cooperation subjects are multi-directional. The ECSNs have three types of network connections for emergency cooperation subjects: vertical, horizontal, and mixed connections. Vertical connection refers to the emergency cooperation between superior and subordinate administrative regions, including the cooperation between the central government and provinces and the cooperation between Beijing, Tianjin, Hebei, and 11 cities in Hebei. Horizontal connection refers to the emergency cooperation between regions at the same administrative level, including the cooperation at the central level, the cooperation between Beijing, Tianjin, and Hebei at the provincial level, and the cooperation between 11 cities in Hebei at the municipal level. The mixed connection refers to the connection inspired by the sudden and complex governance situation, which breaks through the restrictions of levels, regions, and departments, including the cooperation among the JPCM, provincial, and municipal regions.

(3) The structure of the ESCNs is dynamic. The network actors and their relationships in the ECSNs will change with the emergency and finally lead to the network structure with dynamic debugging. That is, the emergency has given birth to the sudden emergence of the JPCM, and resulted in temporary network connections, thereby leading to the structure of the ECSNs under the emergency, and the realization of the dynamic transformation and upgrading of the normal ECSNs.

## 4.2 ECSNs analysis

### 4.2.1 Overall network structure

The calculations of the UCINET shows that 132 connection lines can be found in the ECSNs for COVID-19 between regions in the B-T-H region (Figure 1) with an overall network density of 0.33, indicating a relatively close overall connection. At the same time, the mean value of the central potential of the overall network is 43.75, with a high-value number, indicating that a few subjects in the B-T-H region are in the center of the network, and the power of the ECSNs for magnitude emergencies is relatively concentrated. According to the map of the ECSNs, Beijing, Tianjin, and Hebei are at the center of the social network.

### 4.2.2 Centrality

#### 4.2.2.1 Degree centrality

According to the degree centrality analysis, provincial (municipal) governments are at the center of the ECSNs for COVID-19 in the B-T-H region, and longitudinal coordinated leadership is its dominant mechanism. First, provincial

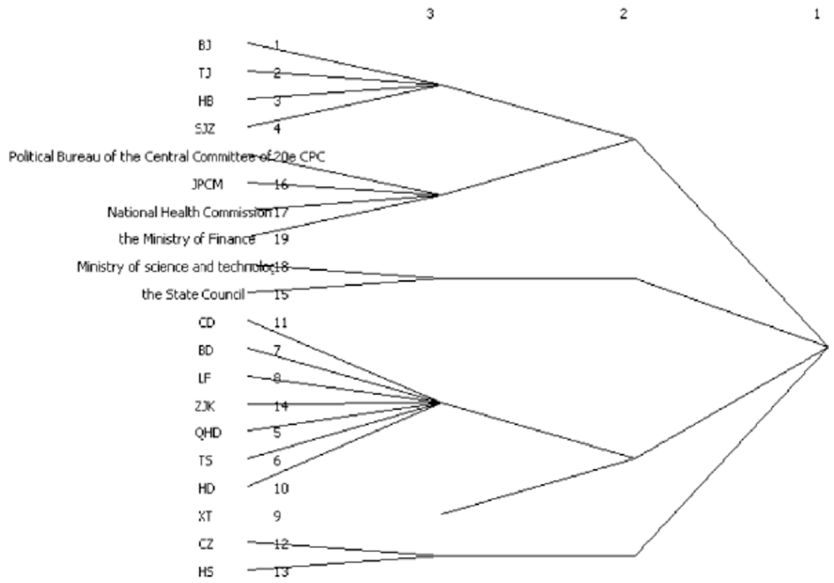


FIGURE 2
Clique analysis of the ECSNs for COVID-19 in the B-T-H region.

(municipal) governments occupy the position of cooperation center. Based on the ranking of the centrality of each subject and the thickness of the connection between subjects in Figure 1, the provincial governments, such as Beijing, Tianjin and Hebei are in the absolute network center position. It shows that the three governments have more power and resources in emergency cooperation, the highest participation and the strongest importance in the ECSNs, and a high degree of emergency cooperation with each other. Second, longitudinal coordinated leadership is its dominant mechanism of emergency management. Here is a response to hypothesis 2. It can be seen that the governance mechanism in the normal governance scenario will have spill over effects on the emergency governance scenario. This phenomenon is caused by the following reasons: 1) the rationality of the bureaucratic system. This point echoes the existing research and reaches a consensus. This system has been continued from the last century to the present, and has been recognized and used by various countries, which proves that it has the rationality of institutional logic. As a governance situation parallel with the normal governance, emergency management can also adopt this governance mechanism. 2) The ECSNs is not yet mature and complete. The situation of emergency governance is not only the same as that of normal governance, but also has higher requirements on governance efficiency and cooperation degree. The bureaucratic system represented by vertical control does not have these advantages, so it is difficult to determine that vertical control is the most suitable governance mode. But due to the present stage countries have not been able to set up flat for emergency management, the collective organization, is also not able to improve the precision of power distribution way, although the organizations established in emergency situations temporary relations of cooperation, but the norm management system still plays a leading role to its, therefore cooperation motivation and persistence are hard to guarantee, It still needs vertical control as the dominant mechanism to guarantee it. Combined with directed relationship, the out-degree centrality of Hebei province and central ministries are significantly higher than the in-degree centrality, which indicates that the Central Government and Hebei province play an important role in promoting intra-network emergency cooperation. At the central level, the National Health Commission and State Council have a high degree of centrality, indicating that the Central Government has a high degree of intervention in emergency cooperation. That is, the vertical promotion and leadership coordination of the Central Government has played a non-negligible role in the formation of the ECSNs. With the exception of Hebei province, the out-degree centrality is greater than in-degree centrality, and the in-degree centrality is greater than out-degree centrality in other cities in Hebei province, indicating that the mechanism of emergency cooperation within the province is top-down leadership and assistance (Table 3).

#### 4.2.2.2 Betweenness centrality

Table 4 shows the betweenness centrality of Beijing, Tianjin, Hebei, and Shijiazhuang is high, accounting for 99.5% of the total. It shows that these organizations occupy the important

TABLE 3 Degree centrality analysis of the ECSNs for COVID-19 in the B-T-H region.

| | OutDegree | InDegree | NrmOutDeg | NrmInDeg |
|---|---|---|---|---|
| BJ | 88 | 67 | 4.4534 | 3.3907 |
| TJ | 97 | 50 | 4.9089 | 2.5304 |
| HB | 867 | 66 | 43.8765 | 3.3401 |
| SJZ | 13 | 143 | 0.6579 | 7.2368 |
| QHD | 3 | 86 | 0.1518 | 4.3522 |
| TS | 2 | 87 | 0.1012 | 4.4028 |
| BD | 2 | 101 | 0.1012 | 5.1113 |
| LF | 2 | 88 | 0.1012 | 4.4534 |
| XT | 5 | 96 | 0.2530 | 4.8583 |
| HD | 2 | 81 | 0.1012 | 4.0992 |
| CD | 3 | 84 | 0.1518 | 4.2510 |
| CZ | 8 | 91 | 0.4049 | 4.6053 |
| HS | 8 | 83 | 0.4049 | 4.2004 |
| ZJK | 2 | 87 | 0.1012 | 4.4028 |
| The State Council | 4 | 0 | 0.2024 | 0.0000 |
| JPCM | 18 | 0 | 0.9109 | 0.0000 |
| NHS | 58 | 1 | 2.9352 | 0.0506 |
| MOST | 1 | 0 | 0.0506 | 0.0000 |
| the Ministry of Finance | 14 | 0 | 0.7085 | 0.0000 |
| Political Bureau of the Central Committee of the CPC | 14 | 0 | 0.7085 | 0.0000 |

TABLE 4 Betweenness centrality analysis of the ECSNs for COVID-19 in the B-T-H region.

| | Betweenness | n-Betweenness |
|---|---|---|
| BJ | 28.4167 | 8.3090 |
| TJ | 5.4167 | 1.5838 |
| HB | 31.9167 | 9.3324 |
| SJZ | 94.7500 | 27.7047 |
| QHD | 0.0000 | 0.0000 |
| TS | 0.0000 | 0.0000 |
| BD | 0.0000 | 0.0000 |
| LF | 0.0000 | 0.0000 |
| XT | 0.0000 | 0.0000 |
| HD | 0.0000 | 0.0000 |
| CD | 0.0000 | 0.0000 |
| CZ | 0.0000 | 0.0000 |
| HS | 0.5000 | 0.1462 |
| ZJK | 0.0000 | 0.0000 |
| The State Council | 0.0000 | 0.0000 |
| JPCM | 0.0000 | 0.0000 |
| NHS | 0.0000 | 0.0000 |
| MOST | 0.0000 | 0.0000 |
| the Ministry of Finance | 0.0000 | 0.0000 |
| Political Bureau of the Central Committee of the CPC | 0.0000 | 0.0000 |

TABLE 5 Closeness centrality analysis of the ECSNs for COVID-19 in the B-T-H region.

| | InFarness | OutFarness | InCloseness | OutCloseness |
|---|---|---|---|---|
| BJ | 26.0000 | 115.0000 | 73.0769 | 16.5217 |
| TJ | 29.0000 | 115.0000 | 65.5172 | 16.5217 |
| HB | 27.0000 | 114.0000 | 70.3704 | 16.6667 |
| SJZ | 21.0000 | 115.0000 | 90.4762 | 16.5217 |
| QHD | 30.0000 | 126.0000 | 63.3333 | 15.0794 |
| TS | 30.0000 | 128.0000 | 63.3333 | 14.8438 |
| BD | 29.0000 | 128.0000 | 65.5172 | 14.8438 |
| LF | 30.0000 | 128.0000 | 63.3333 | 14.8438 |
| XT | 30.0000 | 128.0000 | 63.3333 | 14.8438 |
| HD | 30.0000 | 128.0000 | 63.3333 | 14.8438 |
| CD | 30.0000 | 127.0000 | 63.3333 | 14.9606 |
| CZ | 30.0000 | 124.0000 | 63.3333 | 15.3226 |
| HS | 29.0000 | 124.0000 | 65.5172 | 15.3226 |
| ZJK | 30.0000 | 128.0000 | 63.3333 | 14.8438 |
| The State Council | 380.0000 | 106.0000 | 5.0000 | 17.9245 |
| JPCM | 380.0000 | 96.0000 | 5.0000 | 19.7917 |
| NHS | 45.0000 | 114.0000 | 42.2222 | 16.6667 |
| MOST | 380.0000 | 110.0000 | 5.0000 | 17.2727 |
| the Ministry of Finance | 380.0000 | 96.0000 | 5.0000 | 19.7917 |
| Political Bureau of the Central Committee of the CPC | 380.0000 | 96.0000 | 5.0000 | 19.7917 |

position of bridge nodes and have strong influence and control over other cooperative entities. From the perspective of organizational structure, this may be related closely to its administrative level. The provincial government, as the administrative level between the central and local governments, and Shijiazhuang, as the capital of Hebei province, play an organizational and coordination role, and the characteristics of organizational structure affect its position in the ECSNs.

#### 4.2.2.3 Closeness centrality

Table 5 shows that the ECSNs for COVID-19 in the B-T-H region exhibit the characteristics of close cooperation between provinces and cities with the help of the Central Government. The results of the data analysis show that at the central level, except for the Health Commission, the closeness centrality degree of other organizations is relatively small, indicating that the Health Commission is the main organization promoting emergency cooperation at the central level, and the other organizations play the role of coordination and assistance, located at the edge of the network. At the provincial level, a small gap in the value of closeness to the center can be observed, indicating that the three provinces and cities are closely linked, and the information and resources are interoperable among organizations. According to the background, there are three reasons: 1) The spillover of major public health emergencies forced neighboring regions to cooperate in emergency response. Due to its own characteristics, the COVID-19 pandemic has the characteristics of spillover, which will produce negative externalities on neighboring areas. In the face of local communities of interests, it has created the realistic need for emergency cooperation. 2) The three places have a realistic basis for emergency cooperation. As mentioned above, the three places have signed an emergency cooperation agreement, held regular cooperation meetings, and established a joint prevention and control mechanism to provide stable support for their cooperation. 3) The central government's administrative pressure boosts emergency cooperation. In accordance with the above conclusions, the vertical control mechanism is still the dominant mechanism of emergency cooperation. Therefore, the central government exerts hierarchical capabilities to promote the formation of emergency cooperation.

### 4.2.3 Cohesive subgroup

#### 4.2.3.1 Clique

According to the clique analysis, provinces (municipalities) are the core component of the ECSNs for COVID-19 in the B-T-H region, and regions at the same administrative level are more likely to cooperate and form emergency cooperation. The calculation results of the clique analysis show that there are six cliques in the ECSNs (Figure 2), among which, the first clique composed of Beijing, Tianjin, Hebei, and Shijiazhuang occupies

TABLE 6 Image matrix analysis of the ECSNs for COVID-19 in the B-T-H region.

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1(BJ、TJ、HB、SJZ) | 1 | 0 | 0 | 1 | 1 | 1 |
| 2(NHS ETC.) | 1 | 0 | 0 | 1 | 1 | 1 |
| 3(MOST ETC.) | 1 | 0 | 0 | 0 | 0 | 0 |
| 4(TS ETC.) | 1 | 0 | 0 | 0 | 0 | 0 |
| 5(BD,CD) | 1 | 0 | 0 | 0 | 0 | 0 |
| 6(CZ、HS) | 1 | 0 | 0 | 0 | 0 | 0 |

the core position of the ECSNs and has the closest emergency cooperation among them. In addition, the analysis shows that national ministries, provinces, and cities are more likely to form cooperative relations with regions at the same administrative level.

#### 4.2.3.2 Image matrix

Table 6 shows the results of the image matrix analysis.

First, close links between provinces and cities in Beijing, Tianjin, and Hebei can be observed. From Table 6, the first clique and the fourth, fifth, and sixth cliques are closely connected, indicating a strong bi-directional cooperation willingness among provinces and cities in B-T-H and a close relationship in emergency cooperation. The results show that the normal coordination mechanism in B-T-H produces positive externalities and causes them to overflow in emergencies. The geographical closeness of the three places makes them a community of interest in the face of the epidemic, generating endogenous impetus for emergency cooperation. The high position of the Central Government promotes the increase in the closeness of emergency cooperation.

Second, the emergency cooperation between the Central Government and the region of B-T-H is unilateral resource input and cooperation promotion. From Table 6, the second and third cliques unilaterally show a high degree of closeness to the first clique, which indicates that the cooperation path between the Central Government and B-T-H is top-down resource input and command coordination. Immediately after the outbreak of COVID-19, the Central Government set up the JPCM for COVID-19 and provided instructions and resources to assist the coordinated emergency response in the B-T-H region. These inputs can be categorized as political pressure and emergency assistance exerted by the Central Government on the three regions to promote their emergency cooperation.

Third, cities at prefecture-levels in Hebei do not have close cooperation between cities. Table 6 shows that the 11 cities in Hebei are scattered into three cliques. Considering that the first clique shows a high degree of closeness to the fourth, fifth, and sixth cliques, the emergency cooperation in the province is manifested mainly in the vertical cooperation between provinces and cities, while there is less horizontal cooperation between prefecture-level cities. The main reason is that although the prefecture-level cities in Hebei belong to the same administrative level, the geographical distance is different, and their economic development level differs greatly from the emergency demand. Large differences can also be found in the administrative level, economic development level, and emergency demand between Hebei and its prefecture-level cities. However, the provincial government has political responsibility for the emergency effect on prefecture-level cities because of its administrative subordination in Hebei province. Therefore, in the context of emergency response, political factors break through hierarchical constraints, affect the willingness for emergency cooperation, and political pressure is an important factor in the formation of the ECSNs in the B-T-H region. This responds to hypothesis 2

Based on the SNA analysis of the ECSNs for COVID-19 in the B-T-H region, it can be concluded that the operation mechanism of the ECSNs for magnitude emergencies is multi-directional coordination and cooperation between local governments led by vertical control, and its operation is characterized by multiple subjects, multiple connections, and dynamic structure.

## 5 Asymmetric evolutionary game analysis

The ECSNs are formed by the connection of various emergency subjects and their emergency cooperation relations. The combination of the different strategies among the subjects leads to different cooperative relationships and derives different ECSNs. Therefore, this paper will use an asymmetric evolutionary game to explore emergency strategy selection of each subject in the ECSNs and explore the formation mechanism of the ECSNs.

### 5.1 Basic assumptions

**Hypothesis 1.** Assume that the game subject is the central-provincial-municipal governments in the ECSNs. Local governments (provincial-municipal governments) are the leading force of emergency management, and their strategic choice based on the actual situation determines the cooperative relationship between local governments and other places. And the establishment of emergency cooperation requires at least the combination of cooperative strategies of the local governments of the two places. Therefore, based on the research samples, this paper sets the game subject as the central-provincial-municipal governments in the ECSNs and discusses the selection process of the pair emergency cooperation strategies between them.

**Hypothesis 2.** Both governments adopt two strategies to participate in emergency cooperation, namely, "positive cooperation" and "negative cooperation" (including non-cooperation), namely, the strategy set is {positive, negative}, denoted as $(g1, g2)$ and $(f1, f2)$. The corresponding strategy selection probabilities are $x$, $1 - x(0 \le x \le 1); y, 1 - y(0 \le y \le 1)$.

**Hypothesis 3.** Assume a basic income $R$ used to represent the comprehensive income when both governments adopt positive cooperation strategies in emergency cooperation. When the government of one party is negative in emergency cooperation, the comprehensive emergency income is damaged, and the comprehensive emergency income is set as $\alpha R, (0 \le \alpha \le 1)$. The comprehensive emergency benefit is $\gamma R$ when both parties adopt negative cooperative strategies.

**Hypothesis 4.** :Assume a basic cost $C$ to represent the sum of costs incurred when both governments choose positive strategies. If only one party chooses the negative strategy, that is, the cooperation is not smooth, and the cooperation cost will increase because of the communication and coordination between the two parties. The following two situations may exist: 1) when only one party chooses the negative strategy, the rising cost, $\theta C$, is borne by the party that chooses the positive cooperation and meets the requirement of $0 < \theta < 1$. 2) When both parties choose the negative strategies, both parties need to pay the rising cost$\beta C$, and satisfy$0 < \theta < \beta < 1$.

Hypothesis 5: In the ECSNs, the superior governments retain supervision responsibility for the actions of the subordinate governments. Therefore, if the cooperation is not smooth, the superior governments will punish the governments for the negative cooperation between the two parties. A basic punishment $F$ is assumed to represent the punishment imposed by a superior government for unilateral negative cooperative strategies. When both governments adopt the negative cooperation strategies, the superior government adjusts the basic punishment $F$ through coefficient $\lambda$ $(\lambda \ge 1)$, which is used to punish the two governments.

## 5.2 Model construction

### 5.2.1 Regional asymmetry

In the ECSNs for COVID-19 in the B-T-H region, the administrative level, resources endowment, fragile degree, and degree of geographical approaches of each region differ, making the local governments form an asymmetric relationship between cooperation and dependence and leadership and being led in the emergency cooperation, resulting in widespread asymmetry in the emergency cooperation. This asymmetry is also reflected in the resource-advantageous parties being more likely to occupy a dominant position in emergency cooperation [9], and regional emergency cooperation becomes closer under political pressure. Regions with roughly equal administrative levels and geographically close regions are more likely to form cooperative relationships. The regions hardest hit by the crisis have a stronger willingness to cooperate and receive greater assistance [42]. Therefore, based on the model of asymmetric evolutionary game, this paper discusses the strategy selection and evolution process of local governments in emergency cooperation and attempts to deduce the formation mechanism of the ECSNs.

TABLE 7 Payment matrix of local governments in emergency cooperation.

| Region B (1- k) Region A(k) | Active (y) | Passive (1-y) |
|---|---|---|
| Active (x) | $(R - C)/4k$ | $(\alpha R - C)/4k - \theta C$ |
| | $(R - C)/4(1 - k)$ | $(\alpha R - C)/4(1 - k) - F$ |
| Passive (1-x) | $(\alpha R - C)/4k - F$ | $\frac{\gamma R-(1+\beta)C-\lambda F}{4k}$ |
| | $(\alpha R - C)/4(1 - k) - \theta C$ | $\frac{\gamma R-(1+\beta)C-\lambda F}{4(1-k)}$ |

### 5.2.2 Construction and solution

The choice of local governments strategy includes three cases: 1) Both sides choose the positive cooperation strategy, then the local governments with power value of $k$ can obtain the revenue $(R - C)/4k$, and the local governments with the power value of $1 - k$ can obtain the revenue $(R - C)/4(1 - k)$. The denominator is divided by 4 to return to the traditional equilibrium evolutionary game analysis when $k = 1/2$. 2) Both parties adopt the negative cooperation strategy, and the local governments with the strength value of $k$ can obtain the benefits of $\frac{\gamma R-(1+\beta)C-\lambda F}{4k}$, and the game with the strength value of $1 - k$ can obtain the income of $\frac{\gamma R-(1+\beta)C-\lambda F}{4(1-k)}$. 3) One party adopts a positive cooperation strategy and the other adopts a negative cooperation strategy. There are two situations. First, when region A with a power value of $k$ chooses a positive cooperation strategy, and region B with a power value of $(1 - k)$ chooses negative cooperation strategy, the two regions obtain $(\alpha R - C)/4k - \theta C$ and $(\alpha R - C)/4(1 - k) - F$, respectively. Second, when region A with a power value of $k$ chooses the strategy of negative cooperative, and region B with a power value of $(1 - k)$ chooses the strategy of positive cooperative, the two regions get $(\alpha R - C)/4k - F$ and $(\alpha R - C)/4(1 - k) - \theta C$ , respectively. The payment matrix is shown in Table 7.

The average revenue of local government A is:

$$\overline{V}A = xV_{A1} + (1-x)V_{A2}$$
$$= xy(R-C)\Big/4k + x(1-y)[(\alpha R - C)/4k - \theta C]$$
$$+ (1-x)y[(\alpha R - C)/4k - F]$$
$$+ (1-x)(1-y)\left[\frac{\gamma R - (1+\beta)C - \lambda F}{4k}\right]$$
$$= \frac{x\{R[(\gamma-2\alpha)y - 2\gamma + \alpha] + y(1+4F)\} + [(\alpha-\gamma)Ry + 2\gamma R - C - 4kyF]}{4k} \quad (14)$$

Therefore, the dynamic replication equation of local government A is:

$$F(x) = \frac{dx}{dt} = x(V_{A1} - \bar{V}_A)$$
$$= x(1-x)/4k\{y(R-C) + (1-y)[(\alpha R - C) - 4k\theta C]$$
$$+ y[(\alpha R - C) - 4kF] + (1-y)[\gamma R - (1+\beta)C - \lambda F]\}$$
$$= (1-x)/4k\langle y\{(1-\gamma)R - C + 4k\theta + (1+\beta)C - (4k+\lambda)F\}$$
$$+ \{(a+\gamma)R + \beta C - 4k\theta - \lambda F\}\rangle \quad (15)$$

Similarly, the replication dynamic equation of local government B can be written:

$$G(x) = \frac{dy}{dt} = x(V_{B1} - \bar{V}_B)$$
$$= \frac{y(1-y)}{4(1-k)}\{x[(1-a)R + (4-4k-\lambda)F + (1+\beta)] \quad (16)$$
$$+ [(a-\gamma)R + \beta C - 4\theta(1-k) + \lambda F]\}$$

Analysis of the above dynamic replication equation shows that the system has five equilibrium points (0,0) (0,1) (1,0) (1,1) $\left(\frac{(\gamma-a)R-\beta C+4\theta(1-k)-\lambda F}{(1-a)R+(4-4k-\lambda)F+(1+\beta)}, \frac{\lambda F+4k\theta-(a+\gamma)R-\beta C}{(1-\gamma)R-C+4k\theta+(1+\beta)C-(4k+\lambda)F}\right)$.

$$\text{Set} f(y) = \langle y\{(1-\gamma)R - C + 4k\theta + (1+\beta)C - (4k+\lambda)F\}$$
$$+ \{(a+\gamma)R + \beta C - 4k\theta - \lambda F\}\rangle \quad (17)$$

$$g(x) = \{x[(1-a)R + (4-4k-\lambda)F + (1+\beta)] + [(a-\gamma)R$$
$$+ \beta C - 4\theta(1-k) + \lambda F]\} \quad (18)$$

Further analysis of the Jacobian matrix of the system can be obtained:

$$J = \begin{bmatrix} f(y)(1-2x)/4k & x(1-x)\{(1-\gamma)R - C + 4k\theta + (1+\beta)C - (4k+\lambda)F\}/4k \\ g(x)(1-2y)/4k & y(1-y)[(1-a)R + (4-4k-\lambda)F + (1+\beta)]/4k \end{bmatrix} \quad (19)$$

By calculating the value $Det(J)$and Trace $Tr(J)$ of determinant, it can be seen that (0,0) and (1,1) are not evolutionary stable points (1,0) and (0,1) are evolutionary stable points, and $\left(\frac{(\gamma-a)R-\beta C+4\theta(1-k)-\lambda F}{(1-a)R+(4-4k-\lambda)F+(1+\beta)}, \frac{\lambda F+4k\theta-(a+\gamma)R-\beta C}{(1-\gamma)R-C+4k\theta+(1+\beta)C-(4k+\lambda)F}\right)$is saddle point. Therefore, the evolutionary game phase diagram of positive and negative cooperation between governments is shown in Figure 3.

It is easy to know from the above analysis $(x, y) = \left(\frac{(\gamma-a)R-\beta C+4\theta(1-k)-\lambda F}{(1-a)R+(4-4k-\lambda)F+(1+\beta)}, \frac{\lambda F+4k\theta-(a+\gamma)R-\beta C}{(1-\gamma)R-C+4k\theta+(1+\beta)C-(4k+\lambda)F}\right)$is a mixed strategy Nash equilibrium. In order to better analyze the positive cooperative intention $x$, Let $\mu = \frac{k}{1-k}$ denote asymmetry, then the value of $x$ is converted to:

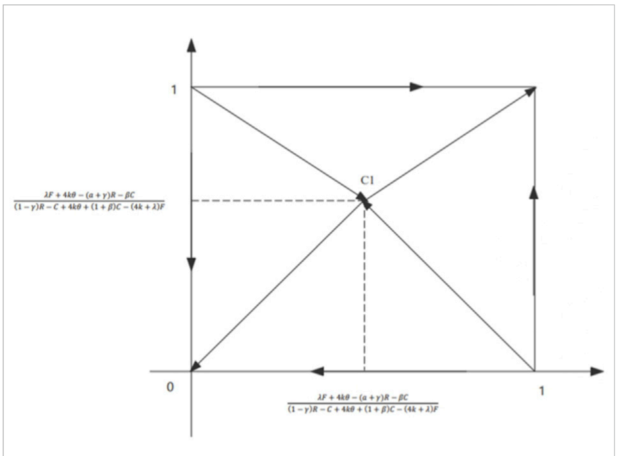


FIGURE 3
Game phase diagram.

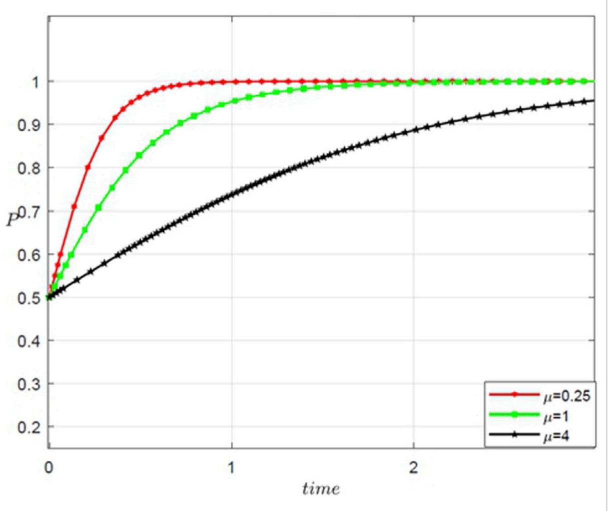


FIGURE 4
The influence of asymmetric ($\mu$) on the evolution of ECSNs.

$$X = \frac{(\mu+1)(\gamma-a)R - (\mu+1)\beta C + 4\theta - (\mu+1)\lambda F}{(\mu+1)(1-a)R + 4F - (\mu+1)\lambda F + (1+\beta)(\mu+1)} \quad (20)$$

Derivative of $\mu$for the expression of region A's positive willingness to cooperate:

$$X'_{(\bar{\mu})} \frac{-\lambda F^2 + [(\gamma-a)R]F + (\lambda\theta - \beta C)F - \theta(1-a) + (1+\beta)}{\{(\mu+1)(1-a)R + 4F - (\mu+1)\lambda F + (1+\beta)(\mu+1)\}^2}$$
$$= \frac{F[-\lambda F + (\gamma-a)R - \beta C + \lambda\theta] - [\theta(1-a) + (1-\beta)]}{\{(\mu+1)(1-a)R + 4F - (\mu+1)\lambda F + (1+\beta)(\mu+1)\}^2} \quad (21)$$

Considering that $0 < \theta, \beta, a < 1$, and $F, R, C \gg \theta, \beta, a$, since $\gamma < a$. So $|[-\lambda F + (\gamma - a)R - \beta C + \lambda\theta]| \gg |[\theta(1 \quad -a) + (1-\beta)]|, F[-\lambda F + (\gamma - a)R - \beta C + \lambda\theta] - [\theta(1-a) + (1-\beta)] < 0, X'_{(\mu)} < 0$

Therefore, the emergency cooperation willingness is inversely proportional to the asymmetric index $\mu$, that is, the larger $\mu$, the smaller the positive emergency cooperation willingness $x$ between the two governments. This responds to hypothesis 1. To analyze the causes of its reality and academic theory, first of all, the different geographical location leads to the similarities and differences of regional cooperation willingness. Geographical proximity is directly proportional to the spillover effect of disasters, so the more neighboring regions have deeper interests in this scenario, the easier it is to reach emergency cooperation. Secondly, the unequal administrative level leads to the similarities and differences in the willingness of emergency cooperation among different regions. The asymmetry of administrative level contains the inequality of political status, especially under the current bureaucratic system, the emergency willingness of vulnerable regions is more easily ignored. Again, differences in cooperation needs lead to differences in emergency cooperation willingness. The need for emergency cooperation is determined by the emergency situation of different places, so the similarities and differences of emergency cooperation needs are inevitable. The greater the need for cooperation, the more likely it is to produce the collective action dilemma of "free riding", leading to the similarities and differences of emergency cooperation willingness.

## 5.3 SD simulation

MATLAB is used to describe the mathematical model of the ECSNs for magnitude emergencies to describe the influence of each parameter value in the ECSNs more intuitively and deduce the formation mechanism of the ECSNs based on the above asymmetric evolutionary game.

### 5.3.1 Influence of asymmetry on ECSNs evolution

First, the influence of asymmetry on the evolution of the ECSNs is explored. On the premise that $0 \le \gamma < \alpha \le 1$, $0 < \theta < \beta < 1$, $\lambda \ge 1$, $0 < k < 1$, assign values to each parameter of the system. Set the initial values as $C = 14$, $R = 22$, $F = 10$, $\alpha = 0.8$, $\gamma = 0.6$, $\theta = 0.2$, $\beta = 0.3$, $\lambda = 1.2$, set the initial value of x and y as 0.5, assign the value of k as 0.2, 0.5, 0.8, respectively, and the running time to [0,3], and then determine the simulation results. The result is shown in Figure 4.

The simulation results show that when $\mu = 0.25$, the evolution of the ECSNs takes the shortest time to reach the equilibrium point, and with the increasing k value, the evolution of the ECSNs takes a longer time to reach the equilibrium, which verifies that the cooperative intention is a subtractive function of the asymmetric value $\mu$ consistent with the game conclusion.

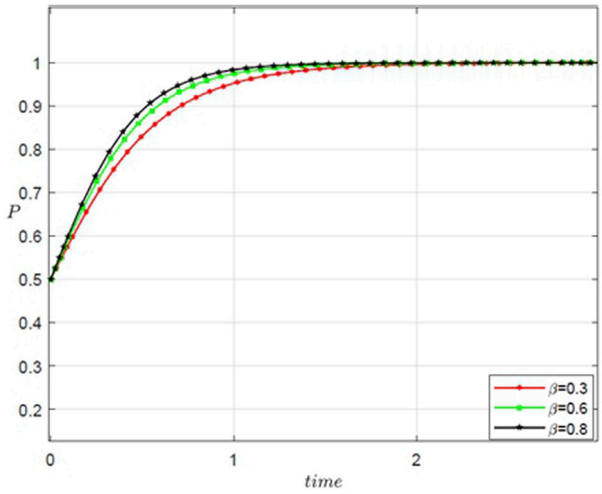


FIGURE 5
The effect of extra cost ($\beta$) on the evolution of ECSNs when both parties cooperate negatively.

### 5.3.2 Effect of extra cost on ECSNs evolution

Cost belongs to the category of economic factors and has always been an important factor affecting the ECSNs. The discussion of the effects of the cost on the evolutionary game is conducive to exploring the effects of the economic factors on the choice of emergency cooperation strategies. Different from traditional evolutionary games, in asymmetric evolutionary games, as long as negative cooperation exists between one party and the other, the emergency cooperation needs to pay extra costs. The simulation of the influence of extra costs on the evolutionary game can directly show the influence of economic factors on the strategy selection of emergency cooperation subjects in the ECSNs. Based on the initial value set, the asymmetry index k was assigned 0.5, When both parties cooperate negatively, the value of additional cost index $\beta$ is 0.3,0.6, and 0.8; When one side cooperates negatively, the extra cost index $\theta$ was assigned 0.2,0.6, and 0.9, respectively, and the running time was [0,3], and thus, the simulation results are obtained (Figure 5,6).

The simulation results show that the extra cost index of the negative cooperation of one party and the negative cooperation of both parties have different influences on the evolution of the ECSNs, and thus, the economic factors have no significant influence on the evolution of the ECSNs for magnitude emergencies. In other words, with the increase in extra cost index $\theta$, the time for the network to reach the evolutionary equilibrium is gradually prolonged when one party is in negative cooperation. When both parties cooperate negatively, the time for the network to reach equilibrium decreases gradually with the increase of extra cost index $\beta$.

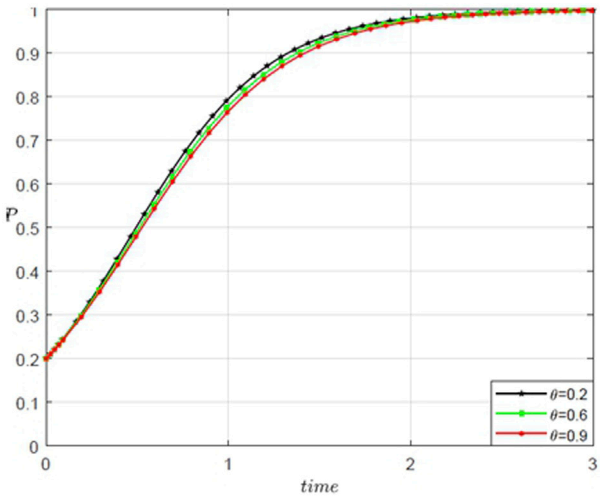


FIGURE 6
The effect of extra cost (θ) on the evolution of ECSNs when one party cooperates negatively.

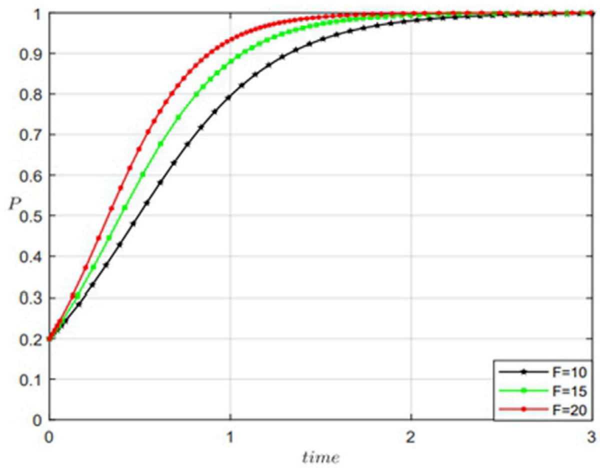


FIGURE 7
The effect of basic punishment *F* on the evolution of ECSNs.

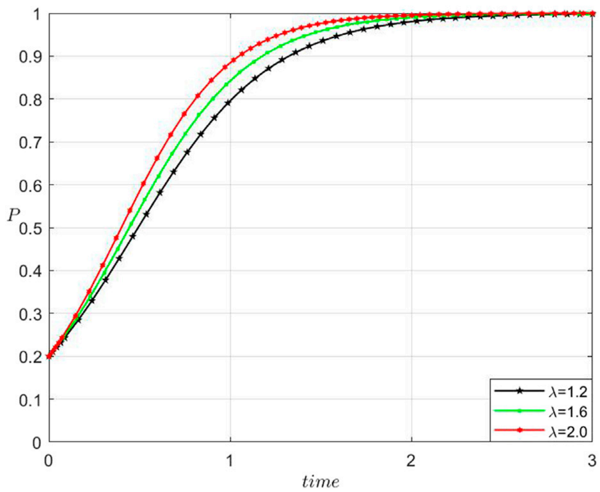


FIGURE 8
The effect of penalty adjustment (λ) on the evolution of ECSNs.

### 5.3.3 Influence of punishment intensity on ECSNs evolution

The punishment of the superior government to the negative partner includes direct administrative punishment, unqualified political performance assessment, blocked promotion of officials, etc., which can be understood as political factors affecting the formation of the ECSNs. The simulation of the influence of punishment intensity on the evolutionary game can reveal the influence of political factors on the ECSNs for magnitude emergencies. The simulation results show that political factors affect the evolution of the ECSNs for magnitude emergencies.

First, to explore the effects of punishment intensity on the evolution of the ECSNs, the basic punishment F was assigned 10,15, and 20, respectively based on the initial value setting, and the simulation results were obtained. Second, when both parties cooperate negatively, the superior government will adjust the basic punishment through the coefficient λ. To fully explore the effect of the punishment on the evolution of the ECSNs, the influence of the punishment adjustment coefficient λ on the evolution of the ECSNs for magnitude emergencies is further simulated based on the SD simulation of the basic punishment. Based on the initial value, the penalty adjustment coefficient λ was set as 1.2, 1.6, and 2.0, respectively, and the simulation was carried out (Figure 7,8).

The simulation results show that the effects of the basic punishment intensity F and punishment adjustment coefficient λ on the evolution of the ECSNs is in the same direction, and thus, political factors will also affect the evolution of the ECSNs. This conclusion is a response to hypothesis 3. In other words, with the decrease of basic punishment intensity F and punishment adjustment coefficient λ, the time for local governments to reach the ECSN is gradually prolonged. Because the punishment of the superior to the subordinate governments can be classified under political pressure, political pressure is inversely proportional to the achievement of the ECSNs. That is, the greater the political pressure, the easier it is to form the ECSNs and the shorter the achievement time.

According to the simulation results, the asymmetry between the subjects in the ECSNs is inversely proportional to the willingness for emergency cooperation. Political factors have a considerable influence on the evolution of the ECSNs, while economic factors have limited influence. Combined with the asymmetric evolutionary game analysis, this paper summarizes the formation mechanism of the ECSNs for magnitude emergencies as follows: the nature of the crisis contributes to the endogenous dynamics of emergency cooperation, while the influence of political factors stimulates the endogenous power to break the asymmetric restrictions and beyond the economic factors, and produces strategic and temporary ECSNs. Among them, the characteristics of magnitude emergencies lead the neighboring area to become a community of interests, generating the endogenous will of emergency cooperation.

The political factors break through hierarchical and economic constraints using coercive means and condense all parties. Thus, external coercive force pressurizes endogenous power, thereby generating the ECSNs.

## 6 Conclusion

This paper takes the B-T-H region in China as a sample and focuses on the emergency cooperation practice for COVID-19. First, massive search data are used to build the ESCNs for magnitude emergencies. Second, the structural characteristics and operation mechanisms of the ECSNs are analyzed using the social network analysis (SNA) method. Third, the asymmetric evolutionary game analysis is used to calculate the subject strategy selection of the ECSNs and the influence of various factors on network evolution is explored through SD simulation to explore the internal mechanism of network generation. Through the above analysis, the following conclusions are obtained:

(1) The ECSNs to meet the emergency needs of countries has been basically formed. With the acceleration of urbanization, human beings enter the risk society, the frequent outbreak of major emergencies has attracted the attention of the governments of various countries, and they have gradually realized the importance of emergency cooperation in the continuous practice of emergency management. Through a long period of continuous development and improvement, all countries have found their own mode of emergency cooperation and formed ECSNs with their own characteristics. Among them, China has formed ECSNs with Chinese characteristics through constant exploration, and played an important role in the prevention and control of the epidemic, which greatly promoted the improvement of the efficiency of emergency management in China. Taking this network as the incision can reflect the general situation of the ECSNs all over the world, and its own characteristics can provide China's experience for the world emergency cooperation. Its network has the pluralism of emergency cooperative subjects, the plurality of the connection of emergency cooperative subjects and the dynamic of the network structure.

(2) The ECSNs for magnitude emergencies have asymmetry, and the cooperative willingness among network subjects is inversely proportional to the asymmetry. First, the asymmetry of the ECSNs is the asymmetry of the subjects in the network in terms of resource endowment, administrative level, geographical distance, emergency demand, political pressure, and so on. Second, the willingness for emergency cooperation with network subjects is inversely proportional to asymmetry, that is, the greater the difference between administrative levels, the easier it is to ignore the willingness of the vulnerable areas in emergency management. The greater the gap in economic development, the more likely the asymmetric distribution of emergency cooperation resources. The greater the difference in demand, the more likely the emergency cooperation to appear as the "free rider" dilemma. Regional emergency management cooperation norms and systems should be formulated through consultation to integrate the interests of all parties in emergency management, eliminate the negative effect of the asymmetry, and promote regional emergency cooperation.

(3) The operation mechanism of the ECSNs for magnitude emergencies is multi-directional coordination and cooperation between local governments under longitudinal hierarchical control. The generation mechanism is that political factors affect the endogenous cooperation willingness, which breaks through the hierarchical and economic constraints and condenses the subject of all parties, generating the strategic and temporary ECSNs. That is, vertical level control is still the dominant mode of the ECSNs. Complex emergencies force the political pressure to break through hierarchical and economic constraints. The characteristics of magnitude emergencies catalyze the endogenous willingness of emergency cooperation in regional communities of interest. External pressure affects the endogenous willingness to produce the ECSNs for magnitude emergency that is dominated by vertical control and supplemented by horizontal coordination. Among these characteristics, political pressure is an important factor influencing the

formation and evolution of the ECSNs, while economic factors have little influence on it. This is because of the emergency management situation of a magnitude emergency on many aspects, such as economy, society, life and property security threat, is a special governance situation with political gravity. The government will take temporary tough measures to rein them in, regardless of the economic cost, resulting in a strategic and temporary form of network governance.

## Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## Author contributions

RN and JW both carefully outlined the contents of the review and wrote the entire manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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