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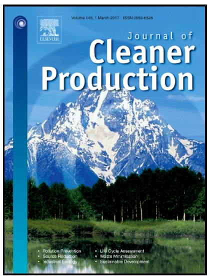

Comparing the vulnerability of different coal industrial symbiosis networks under economic fluctuations

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Highlights

The impact path of economic shock on industrial symbiosis network performance is revealed.

The differences of vulnerability to economic shock among three kinds of network are clarified.

An improved cascading failure model with directed weighted network is proposed.

A promising decision support system for the management of eco-industrial park is provided.

Comparing the vulnerability of different coal industrial symbiosis networks under economic fluctuations

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ABSTRACT

We establish a vulnerability analytical framework of CISN, and illustrate the impact path of economic fluctuation on CISN performance. Based on this, we propose an improved cascading failure model with directed weighted network, and design five network performance indicators (i.e., relative value of cascading failure, average path length, relative value of maximal connected sub-graphs, network efficiency, and structure entropy). Taking three coal eco-industrial parks in China as cases, we simulate and compare the impacts on CISN vulnerability (i.e., equality-based, dependent-based, and nested-based CISNs) of economic fluctuation. The results indicate that the interaction between economic fluctuation and network structure is the key factor in determining system vulnerability. Concerning overall vulnerability, equality-based CISN is highest, dependent-based CISN is next, and nested-based CISN is lowest. Regarding disturbance type, the changes in the five performance indicators of the three types of CISN are more intense under energy price shocks than with declining demand. Moreover, the cascading failure scale of equality-based CISN is greatest with declining demand, while the other two kinds of CISN's is greatest under energy price shocks. Concerning disturbance intensity, equality-based CISN shows initial value sensitivity to economic fluctuation, and nested-based CISN has the strongest tolerances for economic fluctuation. From the network performance perspective, the performance of nested-based CISN is superior to that of dependent-based and equality-based CISNs. Due to longer average path length and lower network efficiency, the failure diffusion trend of equality-based CISN shows the curve of Type-S, and the diffusion rate is smooth and slow. Contrariwise, the initial diffusion rate of dependent-based CISN is the highest, indicating that the loss of system efficiency can somewhat improve the system's anti-risk ability.

Keywords industrial symbiosis network; vulnerability; economic fluctuation; multi-agent based simulation

1. Introduction

The resource flow path of the traditional coal mining industrial system is "coal mining department→ coal supply department→ production department→ transportation department→ consumer group→ natural environment." This one-way linear resource flow has caused serious eco-environmental problems (Kuai et al., 2015). Resource management based on the symbiosis network could realize waste recycling and transform the resource flow from linear to a closed loop network by designing an industrial symbiosis chain and recycling the waste, thus reducing the stress on natural resources and the environment (Li and Wang, 2015; Yu et al., 2015a). There is increasing evidence that firms, governmental agencies, and NGOs throughout the world are seeking to stimulate industrial symbiosis (Boons et al., 2011; Laybourn and Lombardi, 2012). China's central government has focused on

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ecological modernization and made circular economy development part of the national ecological security strategy (Geng et al., 2013). In the last 10 years, more than 40 large-scale mining areas in China have constructed coal industrial symbiosis networks (CISN) by building circular economy parks.

A CISN[2] is formed by optimizing industrial chains vertically and horizontally according to the principle of material cycling and harmonious symbiosis between biology and industry in a coal mining area (Zhang et al., 2013). Compared to conventional eco-industrial parks, the unique industrial connection properties and growth environment of CISN require harsher stability conditions. For example, in the emergence and development of CISN, "geographical proximity" and "organizational proximity", aimed at creating advantages, often lead enterprises to be locked into a specific resource and activity. Moreover, due to the inherent defects of its internal structure and the excessive intervention of local governments, the position and functions of this kind of mining area have been confined to the framework of the energy industry base, which has seriously reduced the industrial diversity of CISN. All these factors restrict the adaptive capacity of CISN in responding to external shocks, and a minor change in economic or environmental factors may paralyze the production and operation of enterprises in the symbiotic chain (Martin and Sunley, 2015). The major CISN industries (e.g., coal, electronics, coal chemical industry) are all fundamental to the national economy. A statistical analysis via the Morgan Stanley Capital International indicator shows that these industries are more sensitive to macroeconomic fluctuations than are other industries. Thus, economic fluctuations play an important role in the healthy development of CISN.

In recent years, many challenge-seeking scholars have spent considerable effort on CISN design (Muduli et al., 2013), evolution mechanism (Van Beers et al., 2007), efficiency evaluation (Kulshreshtha and Parikh, 2002), and resource metabolism (Salmi, 2007). However, the literature shows that studies on the vulnerability of CISNs, especially the impact of economic fluctuations on their vulnerability, are limited. The view that "structure determines function" is basic to systems science, and analyzing system function from the perspective of structure is basic ideas in complex network theory. Based on this research paradigm, we attempt an exploratory study on the vulnerability of CISN under economic fluctuations. This study contributes to the literature in three ways. First, we establish a vulnerability analytical framework for CISN under economic fluctuations and illustrate the conduction relationship of "economic fluctuations→ transformation of business operations→ structural changes of CISN→ function degradation→ performance decline." Second, considering the direction of internal resources flow in CISN and the heterogeneity of the enterprise, we propose an improved cascading failure model with a directed weighted network. This methodology provides a promising multi-agent simulation tool for vulnerability studies on the industrial symbiosis network. Third, through the simulation and comparative analysis, we identify the impacts of energy price shocks and the falling demand on the vulnerability of three types of CISN, thus providing a decision-making reference for the planning, design and stability governance of CISN.

2. Literature review

2.1. The evolution mechanism of industrial symbiosis network (ISN)

Understanding the evolution of ISN will help us grasp whether the system is moving in the direction of

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[2] CISN - Coal Industrial Symbiosis Network; ISN - Industrial Symbiosis Network.

sustainable development. The literature studies the ISN evolution process from the perspective of the formation model of industrial symbiosis or system simulation. Chertow and Ehrenfeld (2012) put forward a three-stage model of industrial symbiosis evolution in self-organizing mode: sprouting, uncovering, and embeddedness and institutionalization. Taking Ulsan Eco-industrial Park as a case, Behera et al. (2012) studied the evolution process of ISN under a top-level programming model. Batten (2009) explored the co-evolution of ISN and how learning influenced it via agent simulation and participatory modeling.

Other studies have discussed the motive force and direction of ISN's evolution. Taking Rizhao Eco-industrial Park as a case, Yu et al. (2015b) analyzed the driving factors of enterprises' participation in a symbiosis network. The results showed that its important drivers were economic benefits, financial subsidies, tax incentives, and material substitution benefits. As industry organizations tend to be complicated, Posch et al. (2011) argued that simple analyses of material flow have failed to meet the demand of development, and the industrial organization should be studied at the symbiosis network level.

2.2. Influencing factors of ISN evolution

The failure of a large number of "designed" symbiosis projects motivated people to determine which factors affect project operation. According to the literature, these factors include policy, system, information technology, and social capital (Spekkink, 2013). Costa et al. (2010) analyzed the influence of waste policy intervention on industrial symbiosis evolution, including flexible waste management policies and regulations as well as strong economic and institutional measures. Salmi et al. (2012) analyzed the effects of the applicability of environmental regulation on industrial symbiosis. Grant et al. (2010) argued that information communication technology played an important role in the formation and development of industrial symbiosis.

The research focus of industrial symbiosis has recently turned to the impact of social factors on the ISN (Doménech and Davies, 2011). Baas (2008) introduced the "embeddedness" concept and analyzed the effects of various dimensions (e.g., cognition, culture, politics, etc.) of embeddedness on ISN. Ashton and Bain (2012) argued that trust in management and social capital strongly influenced the development of industrial symbiosis.

2.3. Stability management strategy of ISN

It is crucial to maintain the stability of the system for the long-term development of the whole symbiosis system. Based on the "system connectivity and diversity" concept in ecology, Wright et al. (2009) studied the calculation method of connectivity and diversity in the industrial symbiosis system to assess its sustainability and stability. Hsu and Rohmer (2010) formulated a dynamic simulation model of system inventory to analyze the stability and reliability of the operation of an industrial collaborative system. Zeng et al. (2013) argued that identifying the key node in the network and ensuring its effectiveness could prevent a chain reaction caused by its failure.

In order to ensure the stability of ISN, It is necessary to choose the appropriate organization form and pay attention to the development of the core enterprise (Conticelli and Tondelli, 2014). Chopra and Khanna (2014) conducted scenario simulation research on the Danish Karen fort industrial park, finding that the overall stability of the ISN had greatly improved since the 1960s. Jiao and Boons (2014) revealed the inner connection mechanism between the stable operation of the ecological industrial park and policy intervention.

2.4. Cascading failure model

Under the impact of economic fluctuations, the breakdown of a tiny number of nodes or edges in a CISN will induce the failure of other nodes through the coupling relationships among them, and lead to the collapse of a number of nodes and even the whole CISN. This is a typical cascading failure phenomenon.

In recent years, many studies on cascading failures pay close attention to analyzing the evolving characteristics of cascading failures and mainly focus on the cascading phenomena in the diverse networks (Bao et al., 2011), the attack strategies (Wang and Rong, 2011), and so on. After that many researchers find that catastrophic events induced by cascading failures can also occur in coupled networks, cascading failures on coupled networks have started to be studied actively and a number of important aspects of cascading failures in coupled networks have been discussed (Cadini et al., 2017; Veremyev et al., 2014; Wang, 2013). According to the existing literature, there are about five types of dynamic cascading failure model for complex networks: the node dynamic network model (Moreno et al., 2002), edge dynamic network model (Moreno et al., 2003), node-edge mixed dynamic network model (Crucitti et al., 2004), sand pile model (Goh et al., 2003), and the cascading failure model based on the coupled map lattice (Zheng et al., 2013).

Extant studies on the stability of ISN suffer from limitations, despite the fact that their achievements provide great referential value. First, from the perspective of research, studies on how energy price shocks and the decline in terminal industry demand amid economic fluctuations influence CISN evolution are rare. Additionally, comparative research on the vulnerability of CISNs with different structures is limited, even though the vulnerability of ISN largely depends on its network structure. Most CISNs in China develop via the intervention of government; thus, their self-adaptive ability are insufficient, and they lack the necessary mature coping mechanism for economic environmental changes. Therefore, in the context of the depth adjustment of the global economy, it is necessary to research the impact of economic fluctuations on the vulnerability of different kinds of CISN. Second, in methodological terms, most of the researches use case studies and theory deduction, which quantitatively reflect the dynamic process of structure evolution poorly. The advantage of using multi-agent modeling to study the economic system is that the emergence phenomenon of macro space can be evolved quickly through the interactions among a large number of individual and simple action rules. The multi-agent modeling approach has been widely applied in various research fields (Albino et al., 2016; Kieckhäfer et al., 2016).

In view of these limitations, based on the cascading failure theory of complex networks, we employ a multi-agent simulation approach to analyze the impact of economic fluctuations on the vulnerability of different CISNs. Through the simulation and comparative analysis, we explore how energy price shocks and the decline in terminal industry demand affect the network performance and vulnerability of various types of CISN.

3. CISN vulnerability analytical framework amid economic fluctuations

According to Mathews and Tan (2011) and Yao et al. (2015), CISN consists of two subsystems: original industrial and extended industrial. The former refers to the production system of the coal mining and coal processing industries. The latter comprises the industries that use coal as raw materials and their corresponding downstream industries, such as the chemical, electronics, building material, metallurgy, and manufacturing industriesk, etc. In recent years, many analytical frameworks have been proposed to explore the vulnerability of the industry ecosystem, such as the Drivers-Pressures-State-Impact-Responses (DPSIR) model (Smeets and Weterings, 1999) and the Exposure–Sensitive–Adaptation (ESA) model (Polsky et al., 2007). Considering the clear causal relationship in the DPSIR framework and the decomposition of the system property in the ESA model, we establish a CISN vulnerability analytical framework under economic fluctuations as shown in Fig. 1.

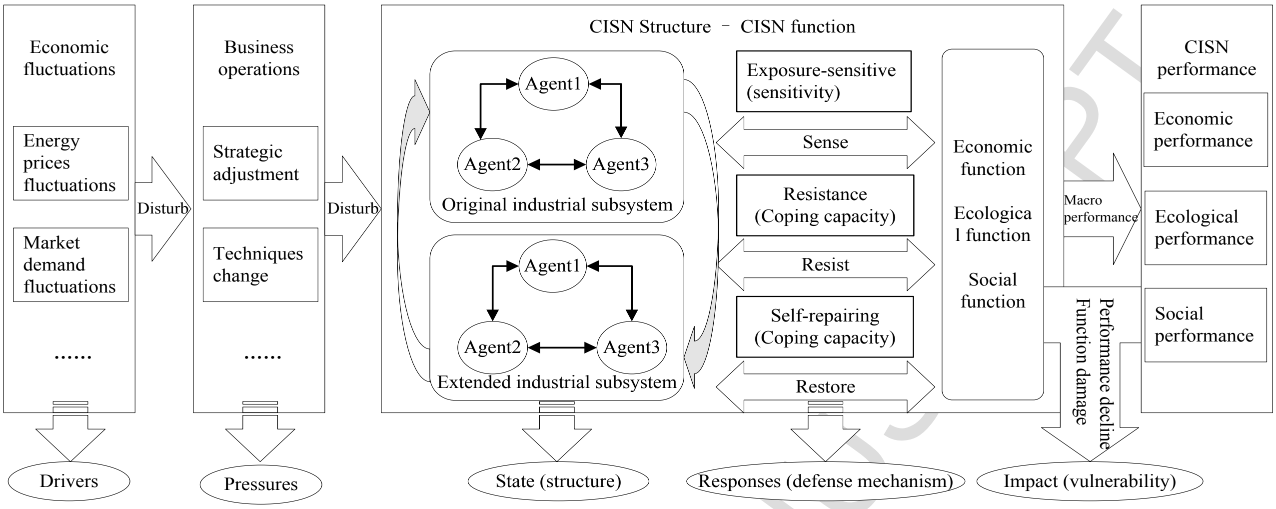


Fig.1 CISN vulnerability analytical framework under economic fluctuations

The CISN perform different functions depending on their structure, and the realization of a special function requires a specific structure. In a relatively stable economic environment, a CISN usually has a strong self-organizing ability. However, when the CISN is exposed to economic shocks, it shows an insufficient adaptive ability. The reallocation of internal economic elements and changes of resource status lead the system's internal structure to evolve in a direction that works against its social, economic, and ecological functions and eventually reduces the social, economic, and ecological benefits of the mining areas. Altering the system's defense mechanism (i.e., perceiving the external changes, taking effective response measures, and performing self-repair) can help the internal structure of the CISN change the function of the system. Therefore, its internal structure is the main factor in CISN vulnerability, and economic fluctuations are the driving factors of the evolution of that vulnerability; these factors can also affect CISN vulnerability by influencing its structure characteristics.

Energy prices are sensitive to changes in the economic environment. Amid economic fluctuations, energy price shocks and a decline in demand will tend to upset the balance of supply and demand among internal CISN bodies and cause adjustments in the CISN's enterprise strategy and production scale. These changes will lead to changes in economic and ecological connection relationships, thus causing adjustments in the CISN's structure, spatial layout, and its relationship with the ecological environment. Without human intervention, the damage to the CISN's internal connections will lead to a decline in its social, economic, and ecological functions. The internal structure of the CISN will evolve through feedback coupling among its system elements and subsystems until it arrives at a new steady state.

In conclusion, we argue that the overall vulnerability of CISN is reflected by the feedback coupling among the agents. CISNs with different internal structures display different vulnerability characteristics, and system vulnerability will evolve along with the changes in the internal structure.

4. Methodology

4.1. CISN structure types and identification methods

In term of the status of enterprises and the ecological and economic relationship among them, CISNs can be divided into three types: equality-based, dependent-based, and nested-based CISNs.

(1) In equality-based CISN, the enterprises mainly depend on equal market transactions, and each manufacturer conducts production with horizontal linkages. The ecological connections of the network are equal, and the economic connections of the network are independent. Specifically, coal-based industries (e.g., power, gasification, coking, and building materials) are connected to each other, and multi-level and multi-channel resource utilization occurs among the enterprises.

(2) In dependent-based CISN, one enterprise or few enterprises are in the dominant position, and the satellite enterprises are in dependent positions. The ecological connection of the network is dependent, and the economic connection of the network is combined. For example, in a dependent-based CISN dominated by the coking industry, coals are washed for coking after being mined. In the coking process, cokes are the main products while a variety of byproducts (e.g., coke oven gas and coal tar) is produced. In this type of CISN, the coke industry is the core industry, and the industries that use the byproducts of the core industry as raw material are dependent.

(3) Nested-based CISN is a kind of symbiosis network between equality-based dependent-based CISN. In a nested-based CISN, there are several leading enterprises, and each one has numerous associated enterprises around them. Therefore, it is a multistage nested network formed by a variety of business relationships among many large enterprises and small and medium-sized enterprises attached to them. This type of CISN features not only vertical industrial chains (e.g., coal→ electric power→ electrolytic aluminum；coal→ gasification→ chemical product，etc.), but also horizontal chains based on the recycling of byproducts and waste (e.g., coal slime→ pyroelectricity；coal gangue→ building materials).

According to Chen et al. (2011), Sun and Wang (2011), and Wang and Yin (2005), we can identify the basic type of a CISN from both enterprise scale and material flow perspectives. In a CISN, industrial metabolism and symbiotic relationship among industries are formed by the vertical extension and horizontal extension of the material energy, and these vertical and horizontal material flows are interwoven into an industrial symbiosis network (Yao et al., 2007). The vertical extension is the deep processing of coal resources, and the forms of material flows based on coal resources mainly include the following: coal→ power; coal→ coal gas→ synthesis gas→ methanol , dimethyl ether; coal→ semi coke; coal→ coal gas→ synthesis gas→ naphtha, gasoline and diesel oil, etc. The horizontal extension is the deep processing of by-products or wastes released by industrial chain of vertical extension, and the forms of material flows based on by-products and wastes mainly include the following: coal gangue, coal slime→ thermal power; calcium carbide→ acetylene→ PVC and polyvinyl; boiler slag, coal gangue→ building materials products; mine water→ industrial, agricultural and domestic water; coal ash→ commodity ash →cement; coal ash→ electrolytic aluminum→ aluminium product, etc. Specifically,

- In equality-based CISN, most enterprises are small and medium-sized enterprises, each one has multi-level and multi-channel material exchange with multiple enterprises, vertical and horizontal material flows are widely existed in each enterprise.
- In dependent-based CISN, the difference of enterprise scale has a great disparity, there is one or a few large enterprises and a number of small and medium-sized enterprises. Material flows from the large enterprise to numerous small and medium-sized enterprises. Vertical and horizontal material flows are existed between the large enterprise and small enterprises, while there is no or just simple material flows among small enterprises, or large enterprises if there is more than one large enterprise.
- In nested-based CISN, there are multiple large enterprises and a number of small and medium-sized enterprises. The material flow of this CISN is more complex in the whole symbiosis network, and it includes one or more vertical and horizontal material flows of dependent-based and equality-based CISN. There are not only vertical and horizontal material flows from large enterprises to small and medium-sized enterprises, but also vertical and horizontal material flows among small enterprises and among large enterprises.

4.2. Study cases

4.2.1 Introduction to three coal eco-industrial parks

In this study, we take three coal eco-industrial parks in China as cases (i.e., Yushen, Dalu, and Lunan Industrial Parks), and build corresponding topological newtork of the CISNs. Yushen Industrial Park is located in north Yulin, the largest coal-producing city in northwest China. In 2014, the proven coal reserves in Yulin reached 150 billion tons, accounting for about 20% of the China's total coal reserves. The park has become China's largest production base for methanol and coal liquefaction synthetic fuel. Dalu Industrial Park is located in east Ordos, the largest coal-producing city in northern China. The first coal-to-oil project in China was constructed in this park in August 2004. Lunan Industrial Park is located in south Jining, the largest coal-producing city in eastern China. The data on the general situation of the three parks were obtained from official websites (www.ysia.gov.cn, www.dlmhg.gov.cn, and www.lnhgcyy.com), respectively. The date on the interrelationship among the enterprises in three coal eco-industrial parks is collected by the authors through field research from March to July 2016, which is supported by the National Natural Science Foundation of China.

Fig. 2 is the brief system network of Yushen Industrial Park. Yushen Industrial Park was built around a large coking plant in the initial stages. By introducing and independently developing technologies about coal gasification and coal liquefaction in recent years, the park gradually formed an industry pattern dominated by coal coking, coal gasification as well as indirect coal liquefaction industries, supported developing the coal chemical deep processing and salt chemical industry, diversified developing the equipment manufacturing industry, new material industry and service support industry. Among that, Shanxi Coke Chemical Co., Ltd., Yanzhou Coal Mining Company Yulin Energy Chemical Co., Ltd., Shenhua Group, Shenmu Oil-rich Energy Technology Co., Ltd. are the representative of large coal chemical enterprises, and others are small and medium-sized enterprises. In the park, there are vertical material flows such as coal →coal gas →synthesis gas →methyl alcohol, dimethyl ether; coal→ semi coke; coal →coal gas →synthesis gas →naphtha, gasoline, diesel, etc. Also there are horizontal material flows such as coal gangue→ thermal power; coal ash→ commodity ash →cement; boiler slag, coal gangue→ building materials products, etc. These material flows nested at multiple levels in the park, there are not only material flows from large enterprises to small and medium-sized enterprises, such as synthetic ammonia →fertilizer; calcium carbide→ acetylene→ PVC, but also material flows among large enterprises, such as coal gas→ synthesis gas; coal tar→ naphtha, gasoline and diesel oil, etc, and also material flow among small and medium-sized enterprises, such as waste textiles→ ceramic; silicon metal→ single silicon→ solar cells , etc. Yushen Industrial Park have typical characteristics of nested-based CISN.

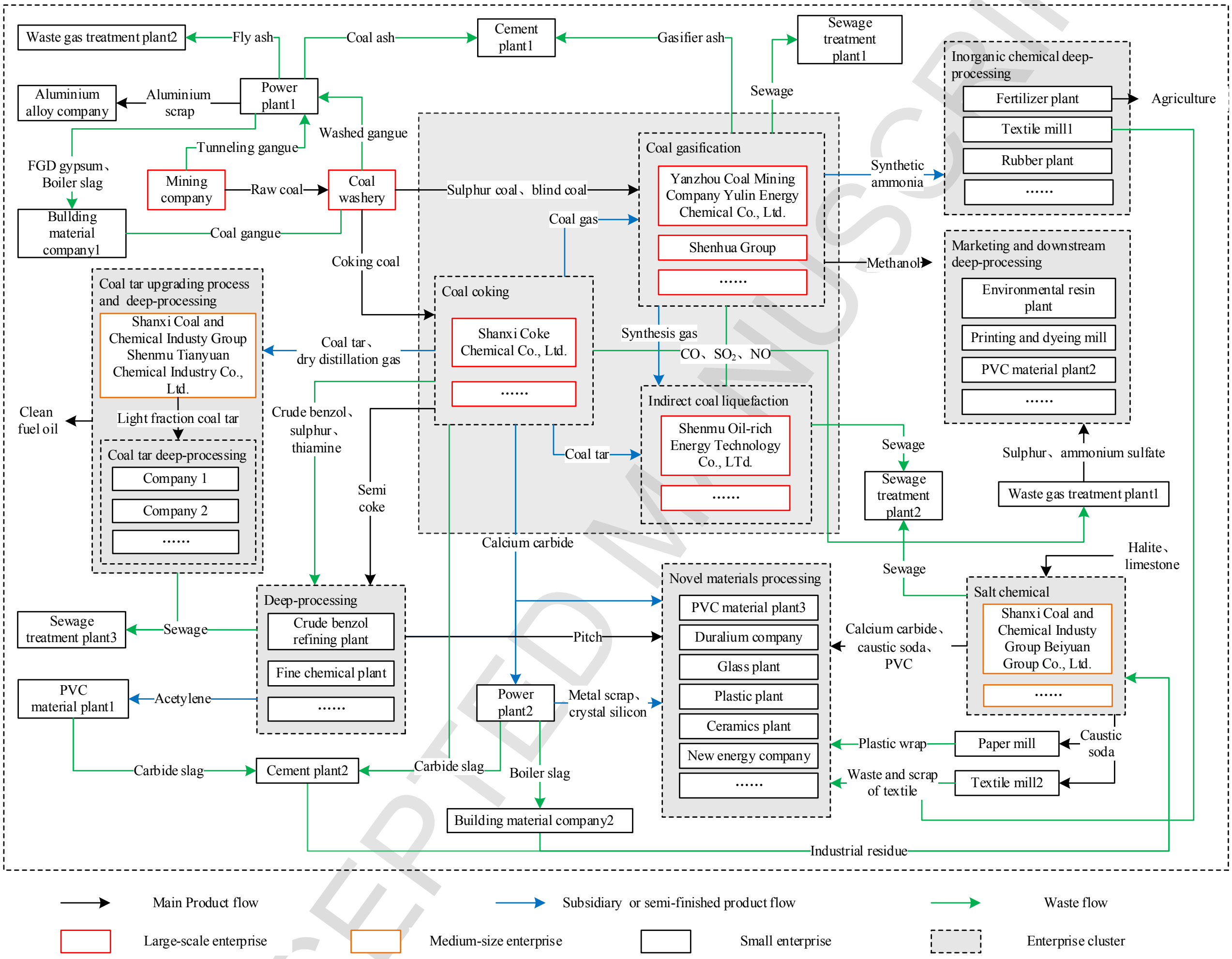


Fig. 2 Brief system network of Yushen Industrial Park.

Fig. 3 is the brief system network of Dalu Industrial Park. Based on the advantage of positioning industry, the park has dominated by coal-electricity and coal-chemical industry, striving to develop coal-chemical downstream fine chemical industry and electrolytic aluminium industry and its deep processing industry, taking the comprehensive utilization of coal residue, fly ash, waste residue, waste gas and waste water as the key, which formed a circular economy industry pattern. Among that, Yitai Group, Jiutai Group, China Power Investment Corporation, CNOOC and Huadian Coal Group are large enterprises. Depending on the large projects of indirect coal to oil, coal to methanol, dimethyl ether, coal to olefin, coal to synthetic natural gas and electrolytic aluminum respectively, they become the core enterprise of the park and a large number of downstream small and medium-sized enterprises build factories around them. The material mainly flow from the core enterprises to small and medium-sized enterprises. There are not only vertical material flows such as coal→ electricity; coal→ coal gas→ synthesis gas→ methanol, dimethyl ether and so on, but also horizontal material flows such as coal residue, coal slurry→ thermoelectricity; boiler ash, coal gangue→ building materials; coal ash→ electrolytic aluminum→ aluminium product; synthesis ammonia→ fertilizer; coal ash→ commodity ash→ cement, etc. The core enterprises are supported by different projects respectively, and there is almost no symbiotic relationship among the core enterprises, and there are only a few simple material flows among the small and medium-sized enterprises, such as industrial wastewater→ industrial water. Dalu Industrial Park has typical characteristics of dependent-based CISN.

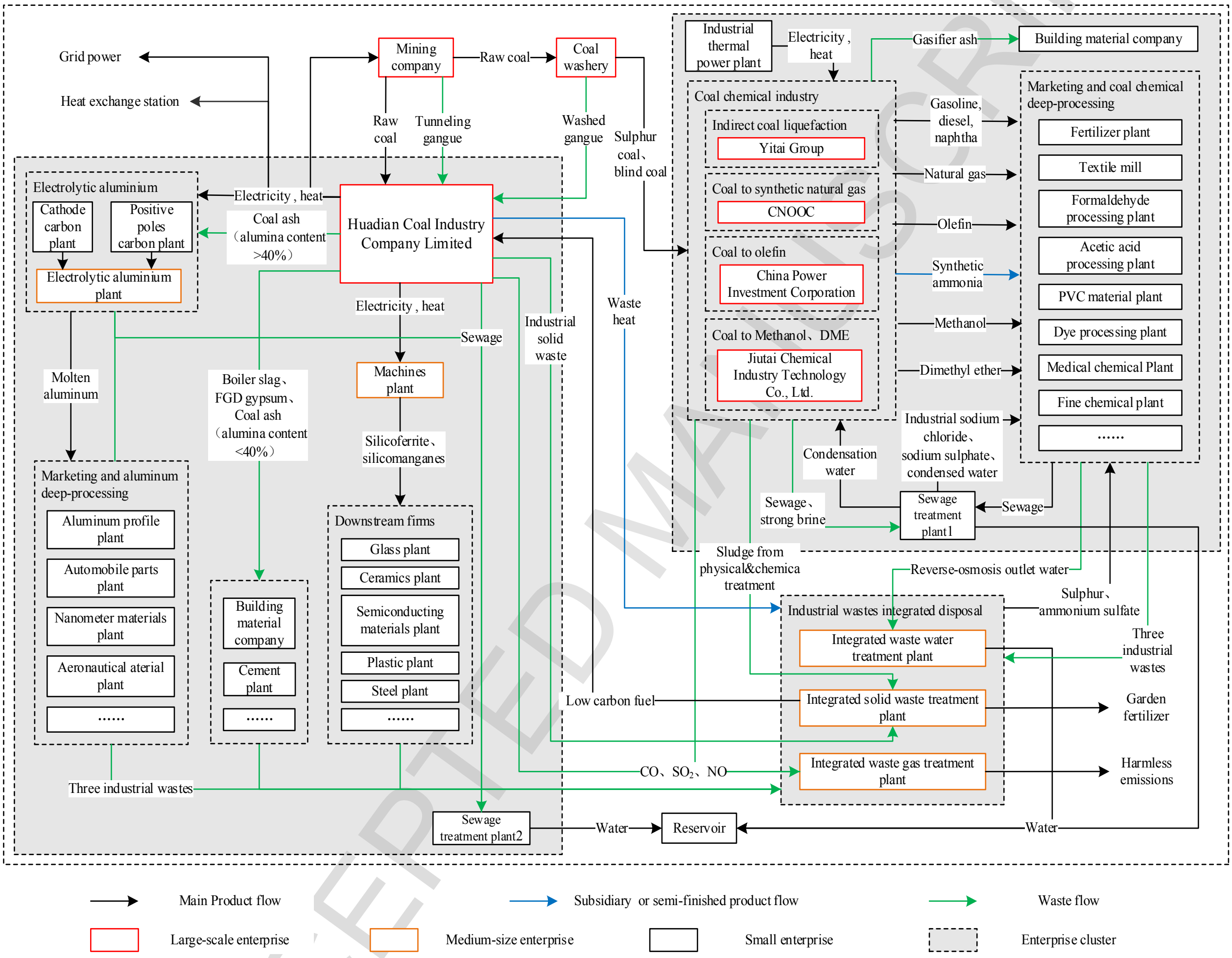


Fig. 3 Brief system network of Dalu Industrial Park.

Fig. 4 is the brief system network of Lunan Industrial Park. Depending on the coal resource advantage, Lunan Industrial Park vigorously promoted the integration of raw materials as well as water resources and the comprehensive utilization of waste from three leading industries of the coal mining, coal-to-chemicals and electrolytic aluminum. More and more companies, such as power plants, coal chemical plants, electrolytic aluminum plants, building materials plants, sewage treatment plants and land rehabilitation companies have set up in the park. These companies are small and medium enterprises, and multi-level and multi-channel resource utilization occurs among the enterprises. Including vertical material flows, such as coal→ power; coal→ gas→ synthesis gas→ methanol, dimethyl ether, etc, and horizontal material flows, such as Coal gangue→ backfill→ land resources; mine water→ industrial water; bauxite→ electrolytic aluminum, etc. Lunan Industrial Park has typical characteristics of equality-based symbiosis networks.

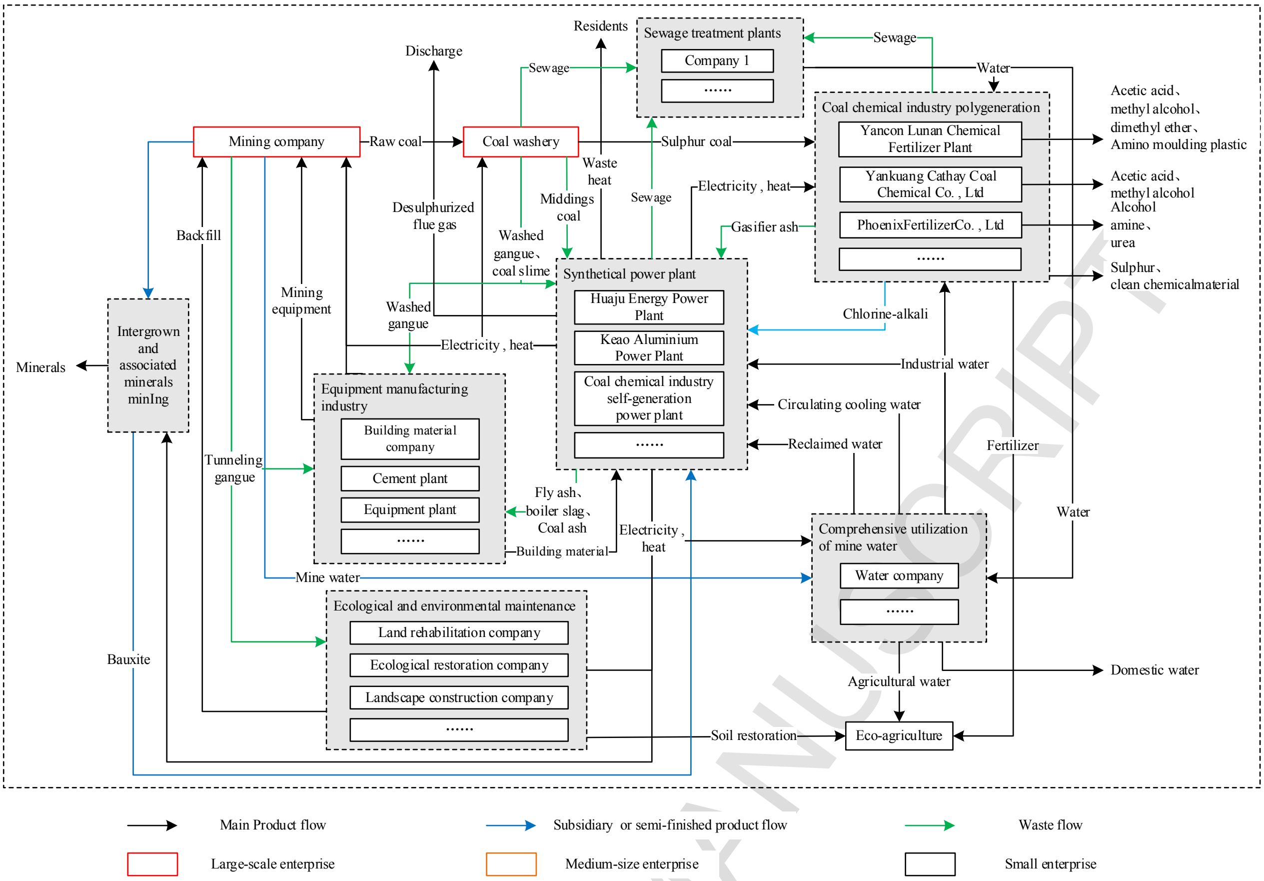


Fig. 4 Brief system network of Lunan Industrial Park.

4.2.2. Topological structures and topological parameters

An adjacency matrix is established according to the interrelationship among the enterprises in the industrial park. Then, a topological structure of the CISN is drawn using the NetDraw tool in Ucinet 6.0. The topological structure charts of Yushen, Dalu, and Lunan Industrial Parks are shown in Fig. 5. The qualitative analysis of the three park's network types were performed in 4.2.1, and the quantitative analysis of the three parks' network type is carried by using the topological parameter. Topological parameter is an effective tool to describe network characteristic. According to Costa et al. (2007), we adopt five parameters (i.e., node-weight distribution, clustering coefficient, structure entropy, average degree, and average path length) to analyze the explicit features of corresponding kind of CISN. These topological parameters of the symbiosis network of the three parks are obtained through programming in Matlab 7.0. The results of topological parameters are shown in Appendix, which are basically consistent with qualitative analysis.

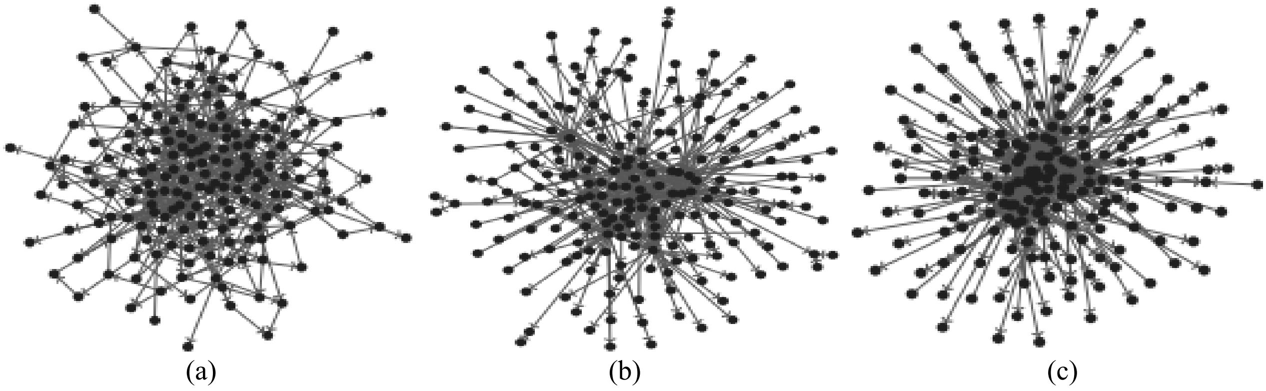

(a) (b) (c)

Fig.5. (a) Topological structure of Lunan Industrial Park, (b) topological structure of Dalu Industrial Park, and (c) topological structure of Yushen Industrial Park

4.3. CISN cascading failure model

In this study, we regard CISN as a directed and weighted network, and establish an improved directed weighted cascading failure model based on the coupled map lattice (CML) model, as shown in formula (1):

$$x_i\left(t+1\right)=\left|\left(1-\varepsilon\right)f\left(x_i\left(t\right)\right)+\varepsilon\sum_{j=1,j\neq i}^{N}a_{i,j}f\left(x_j\left(t\right)\right)/\hat{s}\left(i\right)\right|,i=1,2,\cdots,N \tag{1}$$

Where $x_i\left(t\right)$ denotes the state of node i at time t. The connection information of N nodes is denoted by connection matrix $A=\left(a_{ij}\right)_{N\times N}$. If node i and node j are connected by directed edge $i\rightarrow j$, then $a_{ij}=w_{ij}$; otherwise $a_{ij}=0$. It is specified that there is at most one same-direction edge between any two distinct nodes, and self-join is prohibited. $\hat{s}\left(i\right)$ denotes the initial strength of node i, and $\varepsilon\in\left(0,1\right)$ denotes the coupling strength. The dynamic behavior of a node is denoted by nonlinear function f, and $f\left(x\right)=4x\left(1-x\right)$ is chosen here. The absolute value sign in formula (1) ensures that the state of each node is non-negative.

If the state of node i is always in the range of 0 to 1 within m time series $\left(0<x_i\left(t\right)<1,t<m\right)$, then node i is in the normal state. If $x_i\left(m\right)>1$, then this node breaks down, and the state of this node is equal to zero at any moment in the future; thus, $x_i\left(t\right)\equiv 0,t>m$. The state of each node could be iteratively calculated according to the above formula in the process of CISN evolution. If the initial states of N nodes are all in the range of 0 to 1, and they are not subject to external disturbances, all the nodes will always be in a normal state.

To study the system vulnerability caused by the impact of economic fluctuations on a single or partial node, we exert an external disturbance $R>1$ on node c at time m, as shown in formula (2):

$$x_c\left(m\right)=\left|\left(1-\varepsilon\right)f\left(x_c\left(m-1\right)\right)+\varepsilon\sum_{j=1,j\neq c}^{N}a_{c,j}f\left(x_j\left(t\right)\right)/\hat{s}\left(i\right)\right|+R \tag{2}$$

Node c displays vulnerability at time m. All the nodes connected to node c directly ("neighbor nodes" of node c) are affected by $x_c\left(m\right)$, the state of node c at time m. And the state value of those nodes can be calculated according to formula (2). The calculated state value of those nodes may be greater than 1, thus causing a new round of failure. This diffusion process will run until the CISN reaches a new relatively stable state.

4.4. Analysis indicators of CISN vulnerability

To ensure the reliability of the measurement tools, five indicators are used for reflecting CISN vulnerability.

(1) Relative value of cascading failure (I). Defining relative value of cascading failure to denote the percentage of the failure nodes out of all original network nodes:

$$S=I/N$$

where I is the number of failure nodes after the end of the cascading failure. The sequence diagram of the relative value of failure scale describes the changes in the failure distribution of the CISN's nodes.

(2) Relative value of maximal connected sub-graphs (G).This parameter measures the number of nodes in the maximal connected sub-network of a CISN after the failure nodes are removed. Defining relative value of maximal connected subgraphs G as

$$G=\frac{N^{'}}{N}$$

where $N^{'}$ is the number of nodes contained by the maximal connected subgraphs of CISN after the end of cascading failure. The relative value of the maximal connected sub-graphs reflects the overall connectivity of the CISN.

(3) Average path length $\left(L\right)$.The CISN is not a fully connected network; thus, average path length L is

defined as the mean value of the distance between node pairs with a connected path:

$$L=\frac{\sum_{i=1}^{N}\sum_{j\neq i}d_{ij}}{N(N-1)},GE=\frac{1}{L}$$

where N is the number of nodes in the CISN, d_{ij} denotes a directed path with minimum weights when summed from node i to node j. GE quantitatively reflects the network connectivity efficiency.

(4) Network efficiency (Eff). Eff reflects the transmission characteristics of the resources and information in the CISN. Network topology, routing policy, and traffic information are all associated with Eff:

$$Eff=\frac{1}{N(N-1)}\sum_{i=1}^{N}\sum_{j\neq i}\frac{1}{d_{ij}}$$

where N is the number of network nodes, d_{ij} denotes directed path with minimum weights when summed from node i to node j.

(5) Network structure entropy (E). E is an important state variable reflecting the non-homogeneity of the CISN. The more uniform the distribution of the node importance degree, the greater the entropy.

$$E=-\sum_{i=1}^{N}\left(\frac{s_i}{\sum_{i=1}^{N}s_i}\times\ln\left(\frac{s_i}{\sum_{i=1}^{N}s_i}\right)\right)$$

where N is the number of network nodes, and s_i denotes the weight of node i. To eliminate the effects of N on E, we adopt a standard structure entropy:

$$E=\frac{E-E_{\min}}{E_{\max}-E_{\min}}$$

4.5. Disturbance scene design

Despite the linkage between energy price shocks and the decline in terminal industry demand, there are essential differences between their root causes and in their impacts on CISN. First, regarding root causes, in addition to insufficient demand from downstream industries, China’s energy prices fell sharply due largely to massive excess capacity. The falling demand of the terminal market is due mainly to the decline in exports and insufficient consumption. Second, from the perspective of the transmission mechanism of two kinds of disturbances, declining energy prices firstly influence the core enterprises (e.g., coal mining, coal chemical enterprise) within the CISN, and then affect other enterprises through the coupling relationships. However, the falling demand will firstly affect the enterprises at the end of the CISN industry chain, and then spread to the core enterprises.

Therefore, we emphasize the two aspects of energy prices shocks and the falling demand of the terminal market and simulate the attack strategy of the CISN amid economic fluctuations. We regard the core enterprise with the highest hub score in the three CISNs as the direct target of energy price fluctuations and the enterprise at the end of the industry chain as the target of market demand fluctuations. The simulation occurs by, first, selecting the initial state value of each node in the range of (0.1) randomly and then imposing an external disturbance $R>1$ on several nodes, one at a time. We choose different disturbance objects to distinguish among the disturbance types and adjust the parameter R to control for disturbance intensity. When network node failure stops, the cascading failure ends, and the CISN reaches a new steady state.

5. Simulation results

5.1. Dynamic topology of CISN

We simulate the diffusion process of the cascading failure of the three types of CISN using the NetLogo 4.1. Assuming $R=6$, $\varepsilon=0.6$, the first eight nodes with the greatest weights are selected as the initial attack objects, simulating and analyzing the evolutionary trend of the CISNs' topological structure in the process of realizing the maximum failure scale. The simulation output results are shown in Figs. 6, 7, and 8. A comparison of Figs. 6 (a) and (b) shows that, for equality-based CISN, the network failure under energy price shocks diffuses faster in the early stage, then slows gradually. Under demand changes, however, the diffusion trend of network failure is the opposite. Meanwhile, the final failure scale of equality-based CISN is greater under the disturbance of falling demand than under energy price shocks. A comparison of Figs. 7(a) and (b) shows that, for dependent-based CISN, the network failure diffuses faster and its final failure scale is greater under energy prices shocks. A comparison of Figs. 8(a) and (b) shows that, for nested-based CISN, the network failure diffuses faster under energy prices shocks than under falling demand. Moreover, according to the number of network nodes and edges after the system reached a new steady state, energy price shocks will damage or break more connection relationships among enterprises, although the final failure scale does not differ significantly between the two kinds of disturbance. Overall, a comprehensive comparison among Figs. 6, 7, and 8 shows that, amid energy price fluctuations, the failure diffuses from the center of the network, while, amid demand changes of the terminal market, the failure diffuses from the edge of the network.

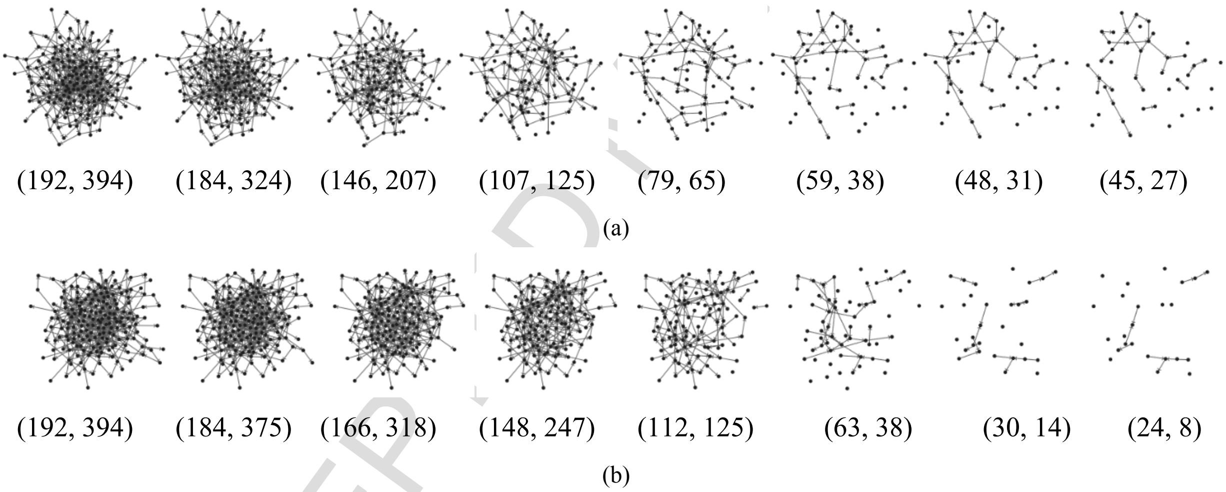


Fig. 6(a) Dynamic topology of equality-based CISN under energy prices shocks, and (b) dynamic topology of equality-based CISN under demand fluctuations

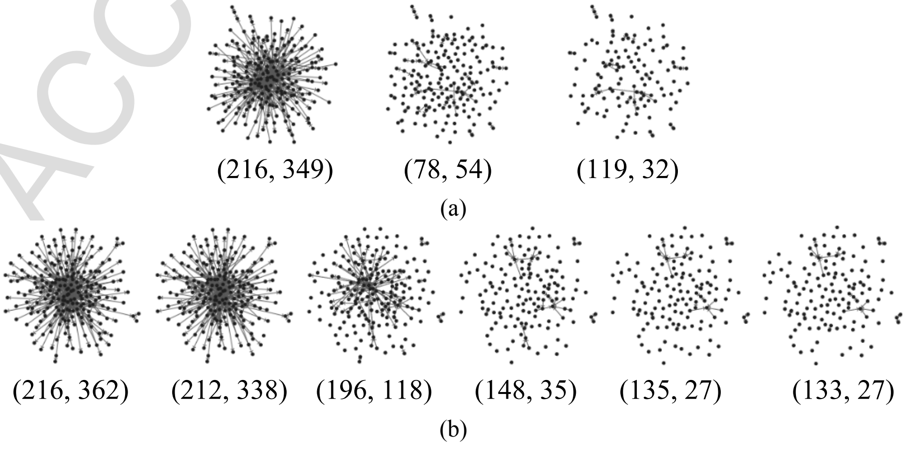


Fig. 7(a) Dynamic topology of dependent-based CISN under energy prices shocks, and (b) dynamic topology of dependent-based CISN under demand fluctuations

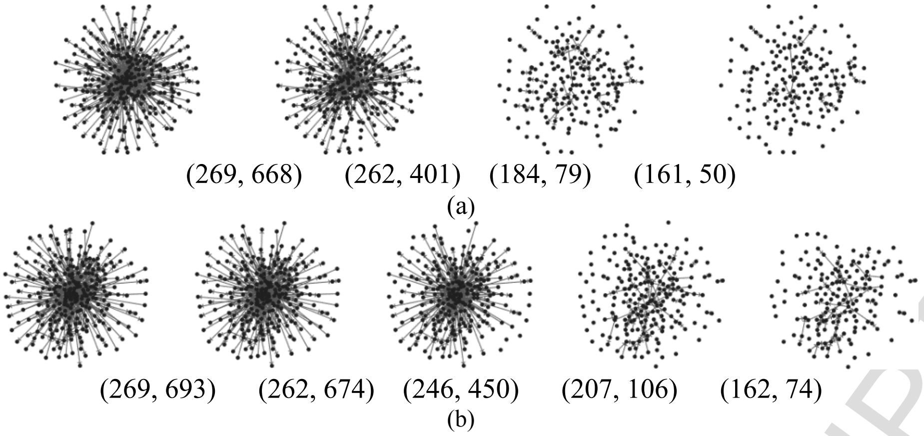


Fig. 8(a) Dynamic topology of nested-based CISN under energy prices shocks, and (b) dynamic topology of nested-based CISN under demand fluctuations

5. 2. Relationship between CISN failure scale and disturbance intensity under different types of disturbance

Assuming $\varepsilon=0.6$, the first eight nodes with the greatest weight are selected as the initial attack objects. We simulate the relationship between the failure scale and disturbance intensity R under different types of disturbance. The simulation results are shown in Figs. 9 and 10.

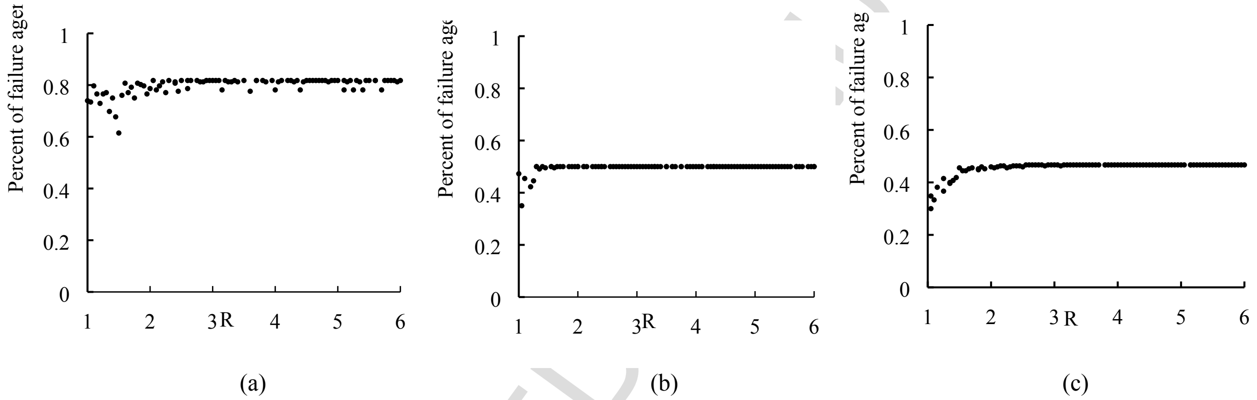


Fig. 9(a) Relationship between failure scale of equality-based CISN and disturbance intensity under energy prices shocks, (b) the relationship between failure scale of dependent-based CISN and disturbance intensity under energy prices shocks, and (c) the relationship between failure scale of nested-based CISN and disturbance intensity under energy prices shocks

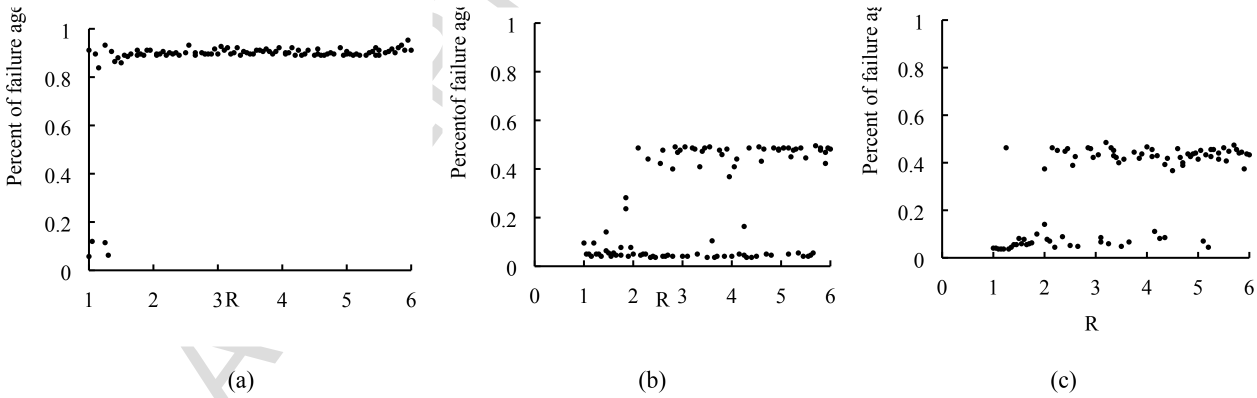


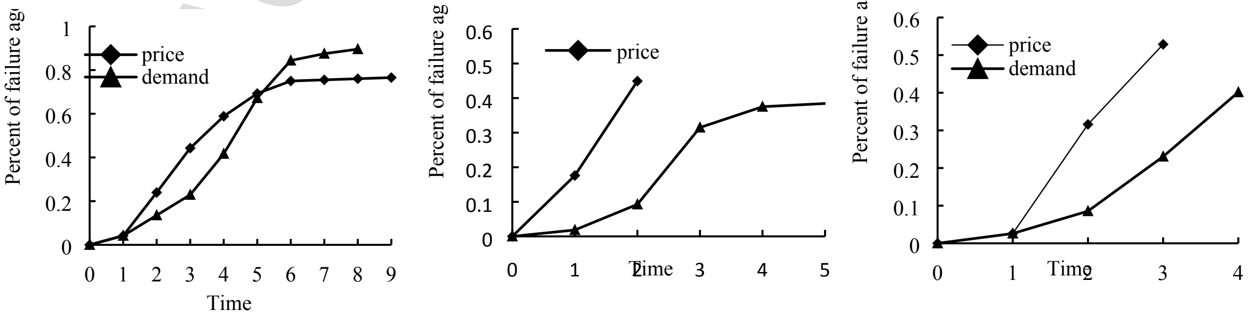
Fig. 10(a) Relationship between failure scale of equality-based CISN and disturbance intensity under falling demand, (b) the relationship between failure scale of dependent-based CISN and disturbance intensity under falling demand, and (c) the relationship between failure scale of nested-based CISN and disturbance intensity under falling demand

First, the differences of sensitivity to disturbance intensity among the three kinds of symbiosis network are compared. Figs. 9 and 10 show that, under two types of disturbance, the final failure scale of equality-based CISN is always greater. Under energy prices shocks, the final failure scales of dependent-based and nested-based CISNs both increase and then become stable. Under falling demand, there is no significant correlation between the failure scale and disturbance intensity. Thus, equality-based CISN displays initial value sensitivity to external disturbance, while dependent-based and nested-based CISNs have stronger tolerances to external fluctuations. However, once system instability occurs, failure spreads rapidly through the connection relationships among enterprises. For all three kinds of CISN, when R attains a certain threshold value, the failure scale stops increasing. Thus, the system failure scale under stronger disturbance can be seen as a measurement indicator of system vulnerability.

Second, sensitivity differences among the three kinds of symbiosis network are compared according to disturbance type. Comparison of Figs. 9(a) and 10(a) shows that the impact of falling demand on equality-based CISN is more intense than is that of energy price shocks. Comparisons of Figs. 9(b) and 10b, and of Figs. 9(c) and 10(c) show that, the impact of energy price shocks on dependent-based and nested-based CISNs is stronger than is that of falling demand. A horizontal comparison of the final failure scale for the three kinds of CISN under the same disturbance intensity thus shows that the vulnerability levels of the CISNs can thus be listed from high to low: equality-based, dependent-based, and nested-based CISNs.

5. 3. Simulation results of failure diffusion characteristics

The simulation results of cascading failure diffusion process of the three CISNs under different types of disturbance are shown in Fig. 11. The triggering time of the largest cascading failure scale is used to reflect the diffusion time of system failure. The change rate of the diffusion degree is used to denote the diffusion rate. First, under energy price shocks and falling demand, the failure diffusion time of equality-based CISN is significantly longer than that of dependent-based CISN and nested-based CISN. Second, a comprehensive study of the failure diffusion time and final failure scale shows that, under energy price shocks, the failure diffusion speed of equality-based CISN is fast in the early period but gradually slows over time. However, under falling demand, the failure diffusion rate of equality-based CISN is initially slow and accelerates gradually; the final failure scale is greater. The evolution law of the failure diffusion rate for dependent-based and nested-based CISNs is largely consistent with that for equality-based CISN. However, the failure diffusion rate and scale of these two kinds of CISN under energy price shocks are slightly higher than under falling demand. The above results indicate that three kinds of CISN are more sensitive to energy price shocks than to falling demand. Finally, comparing among the diffusion rate change trends of the three CISNs shows that the failure diffusion rate of equality-based CISN changes smoothly, but the failure diffusion rate of dependent-based CISN and nested-based CISN changes sharply; moreover, the initial diffusion rate of dependent-based CISN is higher than that of nested-based CISN.

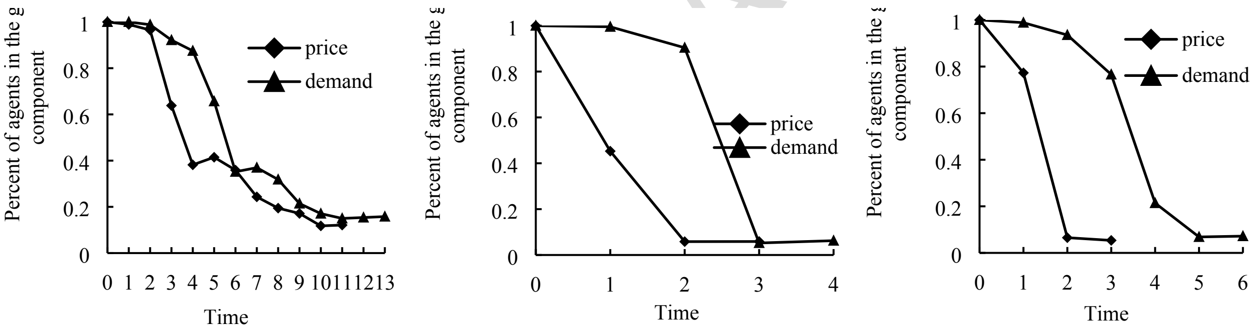


(a) (b) (c)

Fig. 11 (a) Failure diffusion characteristic of equality-based CISN, (b) failure diffusion characteristic of dependent-based CISN, (c) failure diffusion characteristic of nested-based CISN

5. 4. Simulation results of network connectivity

Selecting R=6, ε=0.6, we simulate changing trend of the CISNs' connectivity under different types of fluctuation. The simulation output is shown in Fig. 12. The result shows that, after being disturbed, equality-based CISN can maintain higher connectivity over a certain period of time, and the connectivity of dependent-based CISN and nested-based CISN will rapidly drop. The connectivity of the three kinds of CISN drops faster under energy price shocks than under falling demand. After failure diffusion the connectivity of dependent-based CISN is the lowest, meaning that the final destructiveness of its network structure is at the maximum. For example, in symbiosis network of Dalu Industrial Park, Polyvinyl chloride (PVC) factory is the third largest weight node. When it shuts down, numerous downstream enterprises (e.g., caustic soda plant, organic silicon plant, corrugated pipe factory, etc.) taking the PVC factory products as raw materials will discontinue as well. Then, the linkages between those enterprises and PVC factory will break down, which means that there is no connection between them. However, in symbiosis network of Lunan Industrial Park, though PVC factory is the fourth largest weight node, this park has few dependence on it, and is a typical equality-based CISN. Thus, the thermal power plant can still maintain production and keep in touch with related enterprises when PVC factory shuts down, despite that some of the downstream enterprises of PVC factory will be affected.

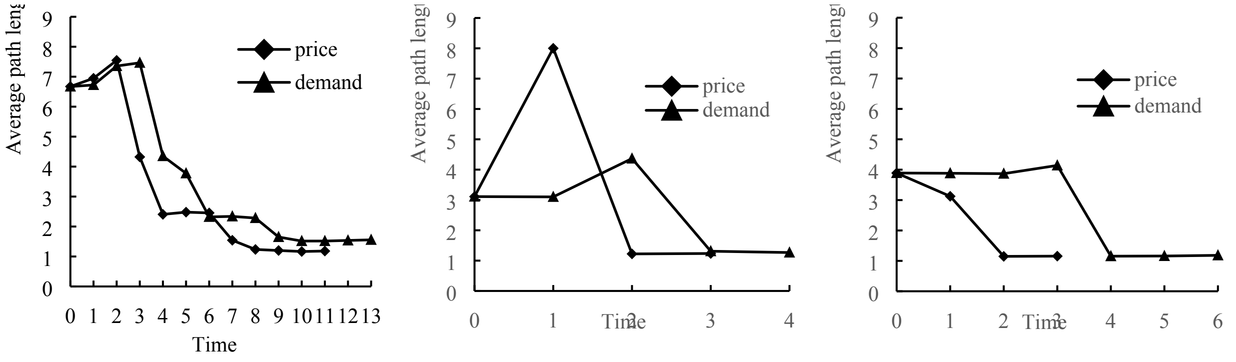


(a) (b) (c)

Fig. 12(a) Network connectivity of equality-based CISN, (b) network connectivity of dependent-based CISN, and (c) network connectivity of nested-based CISN

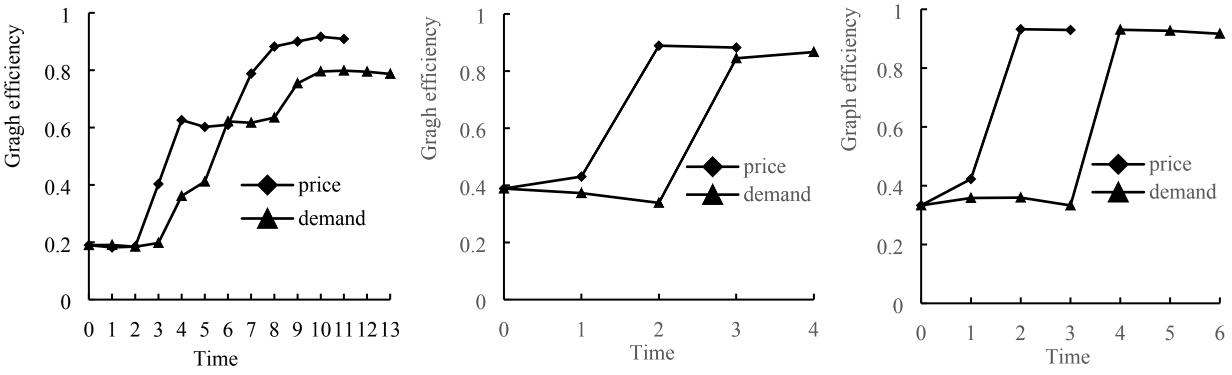
5. 5. Simulation results of network efficiency

Fig. 13 shows the change of the connectivity efficiency, and Fig. 14 shows the change of global efficiency. According to the current definition (i.e., the shorter the average path, the higher the connectivity efficiency), we see that, in the initial state of the network structure, the network connectivity efficiency of nested-based CISN is the highest, dependent-based CISN follows, and equality-based CISN is the lowest. With the transmission and diffusion of failure, the connectivity efficiency of all three CISNs improves. Of course, this improvement comes at the cost of the collapse of a large number of enterprises and the fracture of the relationships between them. Furthermore, under both kinds of disturbance, the connected efficiency of equality-based CISN shows some differences, while the connected efficiencies of dependent-based CISN and nested-based CISN are basically consistent. Fig. 14 shows that, on the whole, the changing trend of network global efficiency is basically consistent with that of network connectivity efficiency, which is represented by the average path length.



(a) (b) (c)

Fig. 13(a) Average path length of equality-based CISN, (b) average path length of dependent-based CISN, (c) average path length of nested-based CISN



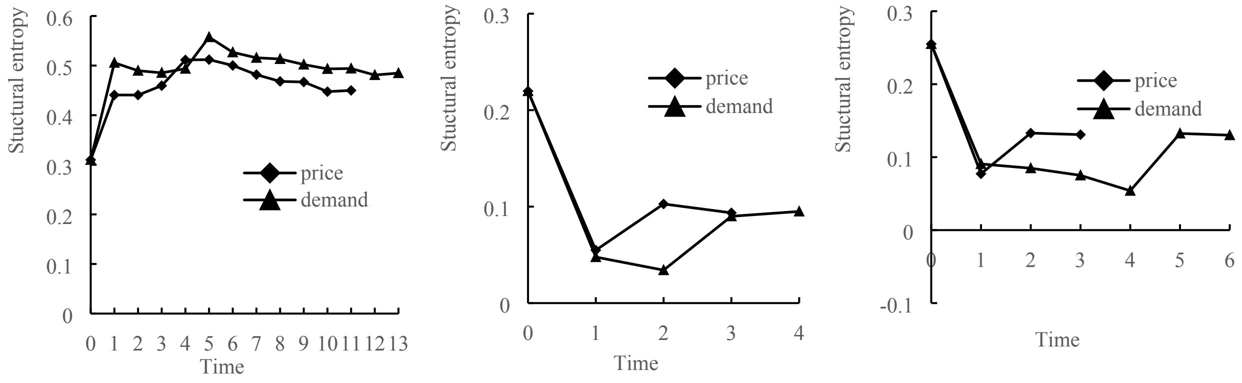
(a) (b) (c)

Fig. 14 (a) Global efficiency of equality-based CISN, (b) global efficiency of dependent-based CISN, (c) global efficiency of nested-based CISN

5. 6. Simulation results of network structure entropy

Fig. 15 shows the change of network structure entropy. For different kinds of CISN, the changing trends of structure entropy differ. With the expansion of the failure scale, under both energy price shocks and falling demand, structure entropy of equality-based CISN increases rapidly at first, and then converges slowly. Structure entropy under falling demand is higher than it is under energy price shocks. For dependent-based and nested-based CISNs, their structure entropy drops rapidly at first, then recovers slightly, and then tends to stabilize under energy price shocks. Under falling demand, network structure entropy first drops rapidly, then drops slowly, then rises slowly, and finally stabilizes. Therefore, with the diffusion of failure, the homogeneity of the equality-based CISN will increase, while the homogeneity of other two kinds of CISNs will decrease.

In the early stage, due to the disturbance of economic fluctuations, the system network structure changes from its original relative steady state to an unsteady state. As a measurement of system disorder, the network structure entropy of the three kinds of CISN all change greatly. In the medium period, the influence of the initial disturbance weakens, but the failure scale still increases, while the change rate of network structure entropy slows. However, because the failure diffusion within CISN is nonlinear, instead of a sustained growth or decline, network structure entropy presents a certain floating increase or decrease. Finally, during the last stage, the network structure tends to be stable, and network structure entropy remains basically unchanged.



(a) (b) (c)

Fig. 15(a) Structure entropy of equality-based CISN, (b) structure entropy of dependent-based CISN, (c) structure entropy of nested-based CISN

6. Discussion and implication

6.1. Discussion

For dependent-based and nested-based CISNs, the core enterprises are in a dominant position. Once the operating condition of core enterprise changes, it will have a great influence on the satellite enterprises and ultimately directly affect the stability of the symbiotic relationship. Within dependent-based and nested-based CISNs, core enterprises are large mining enterprises or coal chemical enterprises. Energy price fluctuations will first trigger the vulnerability of core enterprises. Such a crisis can easily harm many downstream enterprises via the coupling relationships among the enterprises. However, the disturbance objects of terminal demand fluctuations are usually satellite enterprises with less network influence. Their impact on the whole system is relatively small, and the diffusion rate of failure is slow. Therefore, changes in the internal structure of these two kinds of CISN caused by energy price fluctuations are more violent than are those caused by falling demand.

For equality-based CISN, the enterprises possess relative independence, and the symbiosis among them is low. A large amount of material, energy, and information is exchanged between the enterprises and the outside world, but few of them are exchanged within the system. The operations of equality-based CISNs are more dependent on external market demand than are those of dependent-based or nested-based CISNs. Enterprises are often insensitive in the early stage of falling market demand, and dramatic adjustments of production and operations will not be made quickly. The impacts of energy price shocks on enterprise operations differ; energy price fluctuations can affect operating costs quickly, thus forcing the enterprise to adjust its operation strategy quickly. Therefore, equality-based CISNs are more sensitive to energy price fluctuations, but the network failure scale caused by falling demand is greater.

The average path length determines the diffusion time and rate of failure by affecting network connectivity efficiency. The node weight distribution determines the degree of network structure damage by affecting the network's centrality and homogeneity. For dependent-based CISNs, node weight distributions differ, average path lengths are relative short, and network connectivity efficiency is relatively high. When a node (especially the hub node) is attacked, most of the nodes connected to it will be affected, which leads to dramatic changes in network performance. However, the characteristics of network performance indicators are the opposite for equality-based

CISN. Accordingly, the diffusion trend of failure shows the curve of Type-S, and is smooth and slow. Meanwhile, higher network homogeneity implies a large number of redundant relations in the network. The breakdown of redundant relations allows the network performance of equality-based CISN to be maintained for a certain time. This indicates that the loss of system efficiency can somewhat improve the system's anti-risk ability.

6.2. Implication

The results recommend playing a leading role by serving as a multiple core growth pole and enhancing the centripetal force and agglomeration degree of the industrial symbiosis network by cultivating a multiple center. Because enterprises such as coal mining and coal chemical firms have a strong network centrality, the number of relative enterprises should be increased to reduce the dependence on a single core enterprise and maintain the stability of the industrial symbiosis network. The role of the core enterprise cannot be ignored, but excessive support will result in an imbalance of resource allocation. Fluctuations in the operating conditions of this kind of enterprise will have a severe impact on the development of the whole CISN and on the overall stability of the network. In the design and management of CISN, the intensive development trend of network relationship and the development of the symbiosis among different industries should be paid close attention to.

The results also recommend encouraging the nested development pattern and promoting cross-collaboration between industrial chains. This will contribute to the innovation of industrial symbiosis and promote the ability to resist economic fluctuation risks among coal eco-industrial parks. In the design, operation, and management of CISN, local governments should encourage complementary strategic cooperation. The nested development patterns of different industry chains can heighten the accessibility of the industrial symbiosis network and improve its ability to resist selective "attacks." While propelling low-carbon, green, and intensive development, new cooperation platforms and symbiotic relationships should be constructed, and the connections among different industrial chains should be increased. This will extend the industrial chain among enterprises and improve resource utilization efficiency.

Finally, the results recommend promoting the diversity of the industrial ecosystem in coal mining areas. This will weaken the adverse impacts of energy price fluctuations on the CISN. An increased industrial diversity will improve system heterogeneity, and the moderate embedment of competition will boost the adjustment of the network structure and accelerate the improvement of the system function. Moreover, the construction of a pluralistic symbiosis network will intensify connections and cooperation among the heterogeneous stakeholders, and make them dependent on each other. Non-resource-based stakeholders' support of resource-based stakeholders can weaken the effect of energy price fluctuations, thus increasing the environmental adaptive capability of the system. The fragile connections among enterprises is an important factor in the fracture of resource flows in internal CISN and system collapse. Therefore, to ensure CISN stability, all system members should cooperate and form a strong cohesion, thus gaining benefits and realizing stable long-term development.

7. Conclusion and outlook

7.1. Key conclusions

Structure characteristics largely determined the vulnerability of CISNs. According to the final failure scale under the same economic fluctuations, CISN vulnerability levels can be listed from high to low: equality-based, dependent-based, and nested-based CISNs. The vulnerability of equality-based CISN results from its relatively high initial sensitivity to disturbance and relatively long diffusion time of cascading failure, though its diffusion rate of failure is the slowest. Dependent-based and nested-based CISNs have relatively strong tolerances to a certain degree of economic fluctuation. However, as the disturbance intensity increases, failure diffuses quickly in CISN once system instability begins through the economic and ecological connection relationships among the enterprises. Furthermore, the CISNs are all more sensitive to energy price shocks than to falling demand.

Economic fluctuations are the most important driving factor in the evolution of CISN vulnerability. However, the mechanism of this driving factor is to change CISN vulnerability by affecting the CISN network structure. For equality-based CISN, the decline in energy prices and falling market demand both reduce network connectivity, while improving network connectivity efficiency, network global efficiency, and network structure entropy, but the influence of the latter type of disturbance is the more powerful. For dependent-based and nested-based CISNs, these two types of disturbance reduce network connectivity and network structure entropy while improving network connectivity efficiency and global efficiency. The improvement of network efficiency can accelerate failure diffusion in the system and aggravate the damage to network connectivity. In addition, it is contrary to equality-based CISN that the impact of energy price shocks on dependent-based and nested-based CISNs is more powerful than falling demand. Furthermore, the performance of nested-based CISN is superior to that of dependent-based CISN.

7.2. Outlook

Three coal eco-industrial parks in China are studied as cases, and their vulnerability differences under various disturbance characteristics are simulated. However, the simulation of a theoretical model cannot reflect the real evolution characteristics of CISNs perfectly. In future studies, these three coal eco-industrial parks could serve as the objects of long-term tracking experiments to analyze the evolution of their structures and functions, allowing us to examine the reliability of the conclusion in this study by comparing and analyzing the differences among the three kinds of CISN. Moreover, the next step in the research will be to examine how to use the model parameters and government policies in the operation of CISN to decrease network vulnerability.

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Appendix

The node-weight distributions are shown in Figs. A, B, and C. The results of the other topological parameters are shown in Table A.

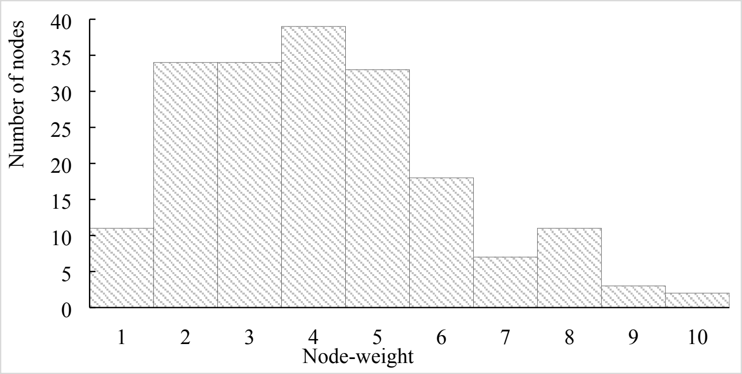

Fig. A Network node-weight distribution of Lunan Industrial Park

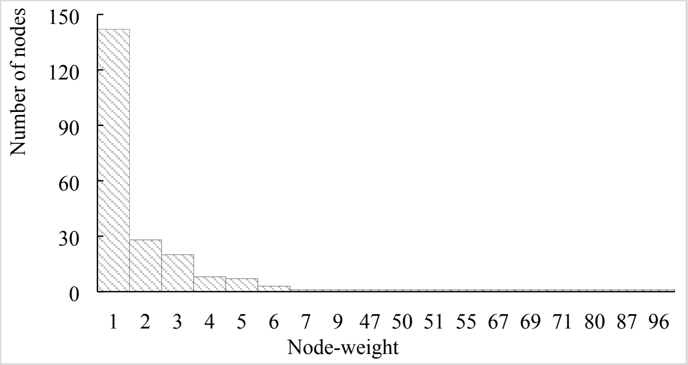

Fig. B. Network node-weight distribution of Dalu Industrial Park

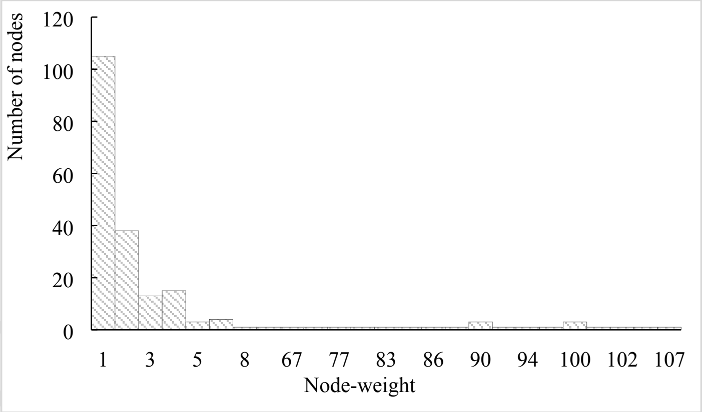

Fig. C. Network node-weight distribution of Yushen Industrial Park

Table A Statistically characteristic parameters of the three CISNs

	Clustering coefficient	Structure entropy	Average degree	Average path length
Lunan Industrial Park	0.0141	1.077	3.836	6.672
Dalu Industrial Park	0.0460	0.282	9.944	3.048
Yushen Industrial Park	0.0215	0.395	4.125	3.991

As shown in Figs.A, B and C, the topological structures of the three coal eco-industrial parks accurately reflects the main characteristics of the three kinds of CISN. As Fig. A shows, the node-weight distribution of Lunan Industrial Park's symbiosis network is a positively skewed distribution, and its skewness and kurtosis coefficients are 0.20 and 1.51 respectively. Thus, the network node-weight distribution is relatively even, and there are no special nodes with large weights. This is consistent with the structural features of equality-based CISN. As Figs. B and C show, the node-weight distribution of Yushen and Dalu Industrial Parks' symbiosis networks obey power law distribution, fully reflecting the growth and advantage accumulation mechanism of enterprises in dependent-based and nested-based CISN. The skewness and kurtosis coefficients of Dalu Industrial Park's symbiosis network are 3.79 and 15.32 respectively, indicating that the operations of many small and medium-sized enterprises are carried out around a core enterprise in the park. This is consistent with the structural features of dependent-based CISN. The skewness and kurtosis coefficients of Yushen Industrial Park's symbiosis network are 4.04 and 18.17 respectively, and there are multiple core nodes, indicating equal symbiosis among large enterprises, dependent-based symbiosis between large enterprises and small and medium-sized enterprises, and mutual infiltration among subsystems in the park. This is consistent with the structural features of nested-based CISN.

According to Table A, we can also come to the same conclusions. First, the clustering coefficient reflects the network centricity. The larger the clustering coefficient, and the stronger the network centricity. The clustering coefficients of Lunan, Dalu, and Yushen Industrial Parks are 0.0141, 0.0460 and 0.0215, respectively, indicating that Dalu Industrial Park has the strongest network centricity while Lunan Industrial Park has the weakest network centricity. Second, structure entropy is an important state variable reflecting the homogeneity of the CISN. The greater the entropy, the higher the network homogeneity. The structure entropies of Lunan, Dalu, and Yushen Industrial Parks are 1.077, 0,282 and 0.395, respectively, showing that Lunan Industrial Park has the highest network homogeneity while Dalu Industrial Park has the lowest network homogeneity. Third, the average degree and average path length reflect the network relationship intensity. The larger the average degree and the shorter the average path length, the stronger the network relationship intensity. Table 3 shows that Lunan Industrial Park has the weakest network relationship intensity, and Dalu Industrial Park has the strongest network relationship intensity. Finally, the values of four parameters of Yushen Industrial Park are all in the middle between those of the other two parks.