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The Vulnerability Assessment Model and Empirical Analysis of Chinese Urban Mineral Industry

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Abstract

Because of the rapid advance of urbanization in China, a serious contradiction has been aroused between city garbage and environmental protection. "Urban mineral" is an industry and the urbanization process of electronic, metal, rubber, plastic and other waste resources recycling. China has approved to construct 49 Urban Mines industry demonstration bases from 2010 to 2015, which indicated that China's urban mines industry has been transferred into social circulation patterns process after experiencing a micro-pattern and park-pattern. With the rapidly progress of industrial process, the urban mineral industry presents some features, for example, the coupling of industrial chain is increasingly close, technology integration and innovation accelerate, affecting factors are more complex, and policy response is more sensitive. All these changes have made the research of industry stability more complicated. In this paper, firstly, we divide the urban mineral system into "marketization, supply, recovery, recycling" sub-systems and analyze the industry relationship by using complex system theory. Secondly, we establish a mutation progression model to describe the key factors and indexes of qualitative change. Thirdly, we introduce both-branch fuzzy set as a kissing subordinate function, which expands the space of value selection and be more comprehensive. We conduct an empirical analysis of the statistical data of the Miluo City Minerals Demonstration Base in Hunan Province from 2009 to 2015.

Keywords: urban minerals, catastrophe progression, risk model, Both-branch fuzzy set, evaluation index

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INTRODUCTION

In March 2013, the State Council's first national-level circular economy development strategy plan was released, marking that China's "urban minerals" industry began to enter the socialized big cycle mode after experiencing the micro-model and park model. In the past 2010-2015 years, China has approved the construction of 49 national demonstration bases of urban mineral resources, and the process of industrial agglomeration has been accelerating. It showed that the coupling of the ecological chain was increasingly tight, the influence factors were complex and the policy response was more sensitive, which made the industrial development in the unstable state and the brittle characteristics were highlighted. Judging from the current research situation, the domestic and foreign scholars' research on "urban minerals" mainly focuses on the micro-industry model, and there is no corresponding special theory on the stability study of the "urban minerals" agglomeration process under the macroscopic macro-circulation model. There are fewer countermeasures. Although relevant scholars have conducted more research on environmental vulnerability, supply chain vulnerability, financial fragility and urban fragility, they do not fully reflect the fragility of "urban minerals" as a static industry. Due to the different industrial characteristics, the relevant research is not widely applicable, and the identification of vulnerability factors is difficult to achieve consistency. At the same time, the fragility of "urban mineral" industry in China is sudden, sensitive, concealed, transitive and time-delay. It involves the main links of resource supply, resource recovery, resource reproduction, resource market, management department and so on, and has formed a relatively stable closed loop industrial chain structure. The classification and quantity of its vulnerability indicators is huge, and the assessment and prevention of its vulnerability risks is a difficult problem. This paper analyzes and establishes the vulnerability model of urban mineral industry system from the four-component subsystem of "supply, recycling, resource and marketization" from the perspective of socialization. The rough set reduction method is used to identify and screen the vulnerability factor. We use the mutation grade method to establish

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the evaluation index and early warning model of urban mineral vulnerability, and combine the both-branch fuzzy set to extend the membership function of the catastrophe series to the fuzzy kissing function. We consider the promotion and inhibition of brittle factors on the evolution of system risk, and expand the space for numerical selection. Thus, the measurement index of the evaluation index is considered comprehensively and objectively. Finally, based on the statistical data of the 2009-2015 7-year statistical data of the Hunan Miluo City Minerals Demonstration Base, and the empirical analysis and comparison of the vulnerability assessment of the mineral bases of 13 major cities in China in 2013, the corresponding conclusions and countermeasures are given.

LITERATURE REVIEW

Urban Mine-UM is an image metaphor for the scale-up development of waste recycling. It originated from the idea of "urban is the future mine" by American urban sociologist Jacobs. The Japanese scholar Nanjo Dolph first defined the concept and basic characteristics of urban minerals in 1988. Subsequently, developed countries represented by Japan, the United States, and Germany conducted a series of studies on urban minerals. The research focused on the analysis of urban mineral composition, reserves, and the analysis of urban minerals (Gowd 2007, Lazarevic et al. 2012, Lowt 2000, Wang et al. 2014, Zaman 2015). Chinese scholar Yang Xianwan first introduced the term (Jacob et al. 2010) and discussed the recycling of scrap metal. In recent years, with the accelerated development of urbanization in China, the pressure on resources and environment has gradually reflected, and relevant research on urban minerals has gradually become a hot issue. Its research work focuses on urban mineral connotation, development, waste management and policy system construction (Guo et al. 2016, Li et al. 2012, 2015, Zhou et al. 2014). Early vulnerability studies focused on the arterial industry, and Timmernan (1981) defined vulnerability as the result of systemic external disturbances as the extent to which the system was adversely affected or damaged. Following Timmernan, Dowing, Cutter and other scholars and the IPCC Fourth Report respectively defined the vulnerability content from different angles (Cutter 1996, Dow 1992). In the 21st century, the research direction of vulnerability began to diversify, and research methods mostly focused on quantitative research methods. At the same time, Chinese scholars interpret the connotation of vulnerability from a variety of research perspectives, with the most typical research on the vulnerability of social systems and economic systems (Li et al. 2015, Yu et al. 2015). Paul and Tang Yan respectively conducted research on the mechanism and model of brittleness caused by complex system fragility theory such as ecological environment deterioration, renewable resources and urban systems (Brunner 2011, Li 2017, Tang 2012). With the acceleration of urbanization, the "Urban Minerals" Industrial Park has a distinct brittle nature as a special corporate spatial organization (Kang and Hu 2012, Wallsten 2015, Wu et al. 2005). Lu and Liu (2012) used the niche measurement to construct the urban mineral vulnerability identification and risk value evaluation model; Xu et al. (2016) combined the relationship of urban mineral industry chain links and used the analytic hierarchy process to evaluate the vulnerability of industrial clusters. Wang et al. (2017), from the perspective of the evolution of China's urban mineral policy, constructed and used the two dimension analysis framework of policy tools - policy role, and discussed the policy guarantee for the stable development of the urban mineral industry. Because the vein industry of urban minerals is greatly influenced by environment, policies and upstream and downstream industries (Zhang et al. 2014) its system's stability, integrity and sustainability are fragile and changeable, which makes it easy for the structure and function of the system to change abrupt or qualitative. At the same time, various sub-links within the urban mine production system and enterprises establish complex dynamic network associations through contract and competition. Therefore, the fragility of the urban mineral industry constitutes ambiguity, dynamics, two-way and abrupt changes (Ding et al. 2015, Wang 2012). Traditional methods of analytic hierarchy process, factor analysis and fuzzy evaluation have great subjectivity or computational complexity (Byron et al. 2011, Lane 2010, Xu and Zhang 2016), which is difficult to reflect the discontinuity and potential abrupt characteristics of urban mineral industry development. The catastrophe theory based on catastrophe theory does not need to use weights for each index, but considers the relative importance of each evaluation index, and obtains the total mutation fuzzy membership function through the normalization of the divergence set. The calculation is simple and accurate. Currently, it is widely used in the comprehensive evaluation process of resource environment, urban development and technological innovation (Navarro et al. 2013). These studies provide convenient tools and theoretical support for the prevention of vulnerability risks in the "urban minerals" industrial system.

CONSTRUCTION OF VULNERABILITY RISK ASSESSMENT INDICATORS FOR URBAN MINERAL INDUSTRY

The "urban minerals" industry has a complex vulnerabilities, often due to unclear responsibility bodies, linearization of recycling systems, delays in industrial chain, inefficient use of resources, and complex dynamics of the industry itself, resulting in instability of internal and external factors. According to the coupling relationship of the ecological chain links of the urban mineral industry, the ecological chain network of the upper, middle and lower reaches of the "urban minerals" industry in China is decomposed into the industrial structure model of "supply, recycling, reproduction and marketization". Based on the theory of industrial agglomeration, new economic geography, and transaction cost theory, the selection of internal and external brittleness factors in industrial systems is carried out. In the process of socialization, these factors interact positively and negatively, thus forming the transmission and restriction of vulnerability between subsystems. We take the industry chain vulnerability risk function as $S = F(Q, R, E)$, where Q is the vulnerability factor, R is the coupling relationship between factors, and E is the system's ability to resist risks. The four industrial subsystem links have their own brittleness factors. ① Supply subsystem: including the current level of manufacturing development, the average purchasing power of the society, and the degree of openness; ② recycling subsystem: including regional location, network channel maturity, logistics level, local policies and protection, and the quality of employees; ③ Reproduction subsystem: including enterprise scale, technical capability, asset allocation and equipment capabilities; ④ Marketization subsystems: including economic scale, enterprise management level, labor cost, and employee education level. These fragility factors also contain a large number of qualitative and quantitative indicators, such as indicators reflecting the ability of the company's asset allocation: fixed assets, asset-liability ratio, profit, product sales and cost-cost utilization. For example, the recycling and marketization subsystems include repetitive factors such as policy system, logistics level and employee level. At the same time, the lower transportation cost has a positive effect on the development of the industry, but the low-cost and inefficient transportation will cause secondary pollution in the transportation, so it has the two-way influence of promotion and suppression. In summary, the system fragility factor indicator is shown in **Fig. 1**. Some of these fragile factors are repetitive, concealed, delayed, linked, bidirectional and mutated.

Table 1. Urban mineral industry vulnerability structure

	Subsystems		Factor	Index
System fragile factor structure	Supply subsystem	Resource endowment	Proportion of reproduction resources	D1
			Obsolete resource utilization	D2
		Industry development level	Industrial production value	D3
			Industrial production growth rate	D4
			Industrial production profit	D5
		Spending power	Population density	D6
			Per capita consumption level	D7
	Recycling subsystem	Channel network	Regional location	D8
			Number of employees	D9
			Market coverage	D10
		Logistics capacity	Railway transportation capacity	D11
			Road transport capacity	D12
			Port transportation capacity	D13
		Policy	Openness	D14
			Government support	D15
			Policy implementation efficiency	D16
	Reproduction subsystem	Technical skills	Technological innovation capability	D17
			Industrial waste utilization	D18
			Technical basis capability	D19
		Business scale	Fixed asset size	D20
			Current assets status	D21
			Number of companies	D22
			Equipment status	D23
	Marketization subsystem	Management level	Policy implementation efficiency	D24
			Information technology sharing degree	D25
			Manager education level	D26
			Labor cost	D27
		Market environment	Opening degree	D28
			Logistics Infrastructure	D29
			Market channel coverage	D30
		Economic scale	Gross industrial output	D31
			Leading product coverage	D32
			Industrial structure similarity	D33
			Consumer purchasing power	D34

The traditional analytic hierarchy process, entropy method and fuzzy evaluation method have the defects of subjectivity and computational complexity in the selection of index weights. In this paper, the catastrophe progression is selected as the risk assessment method, and the rough set is used to reduce the brittleness factor.

It can be seen from **Table 1** that there are many factors affecting the risk of urban mineral vulnerability, which is easy to cause evaluation errors. For example: ① brittleness factor is easy to cause evaluation error due to overlapping information, content or range; ② Due to the limitations of industrial characteristics and data collection, the index weighting is subjective and the index value cannot reflect the degree of influence. Therefore, this paper firstly uses the rough set attribute reduction method to reduce the index, and uses fixed effect analysis to establish the order of importance of each index, which is convenient for subsequent analysis.

Rough set theory is a mathematical tool that can quantitatively analyze and process inaccurate,

Table 2. "Urban mineral" industry vulnerability factor index

Targets	Criteria layer	Factor layer	Indicator layer	Indicator description
Urban mineral industry system vulnerability index	Supply subsystem A1	Manufacturing development level B11	Manufacturing GDP C1 Manufacturing production growth rate C2 Manufacturing profit total C3	Promoting factor Promoting factor Promoting factor
		Consumer purchasing ability B12	Population density C4 Per capita consumption purchasing ability C5 Per capita income C6	Two-way factor Promoting factor Promoting factor
		Resource endowment B13	Recycled resources ratio C7 Obsolete resource utilization C8	Promoting factor Promoting factor
	Recycling subsystem A2	Economic Geography B21	Logistics Infrastructure Level C9 Logistics cost C10 Network channel coverage C11 Number of employees C12	Promoting factor Two-way factor Promoting factor Two-way factor
		Policy system B22	Opening degree C13 Policy support C14 Policy implementation efficiency C15	Two-way factor Promoting factor Promoting factor
	Reproduction subsystem A3	Enterprise size B31	Number of companies C16 Total fixed assets C17 Liquidity scale C18 Production Equipment Status C19	Promoting factor Promoting factor Promoting factor Two-way factor
		Technical ability B32	Industrial waste utilization rate C20 Advanced technology use ratio C21 Technological innovation and number of inventions C22	Promoting factor Promoting factor Promoting factor
	Marketization subsystem A4	Management level B41	Proportion of employees in higher education C23 Labor cost C24 Manager Education Level C25 Information Technology Usage C26	Promoting factor Two-way factor Promoting factor Promoting factor
		Economic size B42	Annual GDP output value C27 Leading product coverage C28 Industrial structure similarity C29	Promoting factor Promoting factor Inhibiting factor

inconsistent, incomplete information and knowledge. Among them, attribute reduction is an effective method for processing data and has been widely used in information processing. In the attribute expression, we can select some attribute values that have little effect, and delete these attributes without affecting the expression of the equivalent relationship. In this paper, the internal correlation factors of the four subsystems in **Fig. 1** are decomposed, the data is discretized by K-means clustering, and the attributes are reduced by rough sets. The secondary indicator channel network of the recycling subsystem overlaps with the market environment presence factor in the marketization subsystem, such as D8 and D29, D10 and D30; There are factor redundancies in the consumption capacity in the supply subsystem and the economic scale in the marketization subsystem, such as D7 and D34; Due to data statistics difficulties and policy factors, the logistics capabilities D11, D12, and D13 in the recycling subsystem can be combined with D8 in the channel network indicator and D29 in the market environment indicator to adjust to the economic geographic secondary indicator. The specific reduction includes 9 secondary indicators and 29 tertiary indicators. According to the econometric model constructed in reference (Li et al. 2012) and the research in the literature (Dow 1992), the fixed effect verification and independent influence degree verification are applied to the factors of appeal. The rankings of the impact of index variables on system vulnerability are as follows: firm size > policy system > industrial development level > technical ability > management level > economic geography > economic scale > resource endowment > consumption purchasing power. Based on this reference as a brittleness factor importance setting, more precise guidance is provided for the analysis of the catastrophe progression. See **Table 1** for the specific secondary indicators and tertiary indicators and their impact relationships.

RISK ASSESSMENT MODEL BASED ON DOUBLE-BRANCH FUZZY CATASTROPHE SERIES

In 1972, French mathematician Rene Thom founded the theory of catastrophe, which was developed on the basis of system structural stability theory, topology and singularity theory. When there are no more than 4 control variables, there are 7 catastrophe forms of the potential function. The commonly used catastrophe models are shown in **Table 3**. The state variable x reflects the behavior state of the system; f(x) is the potential function of the state variable x, and the coefficients a, b, c, d are the control variables of the state variable x, and the order represents the importance of the control variable. Since the catastrophe progression method does not need to use weights for each index, but considers the relative importance of each evaluation

Table 3. The model of elementary catastrophe

Catastrophe model	Control variable	Potential function	Normalization
Folding catastrophe	1	$f(x) = x^3 + ax$	$x = a^{1/2}$
Point catastrophe	2	$f(x) = x^4 + ax^2 + bx$	$x_a = a^{1/2}, x_b = b^{1/3}$
Swallowtail catastrophe	3	$f(x) = x^5 + ax^3 + bx^2 + cx$	$x_a = a^{1/2}, x_b = b^{1/3}, x_c = c^{1/4}$
Butterfly catastrophe	4	$f(x) = x^6 + ax^4 + bx^3 + cx^2 + dx$	$x_a = a^{1/2}, x_b = b^{1/3}, x_c = a^{1/4}, x_d = b^{1/5}$

index, and obtains the total catastrophe fuzzy membership function through the normalization of the divergence set, its calculation is simple and accurate. It has the incomparable advantages of analytic hierarchy process, factor analysis method and fuzzy evaluation index.

Both-Branch Fuzzy Kissing Function Design

According to the brittleness factor of **Table 1**, some factors promote the fragility evolution of the system, some have a two-way effect, and even some factors have an inhibitory effect. Therefore, before using the mutation series evaluation analysis, the both-branch fuzzy membership function kissing function is used to expand the space of numerical selection to improve the measurement effect and accuracy of the evaluation index.

Definition 1: Let U be the domain, S be the both-branch fuzzy set defined on U, and the element x_i and S on U satisfy the relationship $S(x_i) \in [-1,1]$, there is a mapping: $S: U \to [-1,1], x \to S(x)$. $S(x)$ is the fuzzy kissing function on the both-branch fuzzy set S.

Definition 2: In the domain U, U^+, U^-, U^* are called upper domain, lower domain, and local domain of the fuzzy set. If it exists:

1) $\forall x_i \in U^+$ and satisfies $0 < S(x_i) \leq 1$, then $S(x_i)$ is the fuzzy set of the upper branch;

2) $\forall x_k \in U^*$ and satisfies $0 < S(x_k) \leq 1$, then $S(x_k) = 0$ is an indeterminate set;

3) $\forall x_j \in U^-$ and satisfies $-1 \leq S(x_j) \leq 0$, then $S(x_j)$ is the lower fuzzy set.

In the evaluation process of complex system risk mutation series, let i, j, k be the elements in U^+, U^-, U^* respectively, and there are n brittleness factors in system state V, and satisfy $i + j + k = n$. When a subsystem in the system positively promotes the expected evaluation target and suppresses the vulnerability risk of other subsystems, the brittle factor is recorded as $X^+ = \{x_1, x_{2,} \cdots, x_i\}$, which is called the promotion factor; otherwise, it is called the inhibition factor and recorded as $X^- = \{x_{i+1}, x_{i+2,} \cdots, x_j\}$. When some factors have a two-way effect on the evaluation of the target system, it is called the uncertainty factor and is recorded as$X^* = \{x_{j+1}, x_{j+2,} \cdots, x_k\}$. The relationship between these factors can be shown in **Fig. 1**.

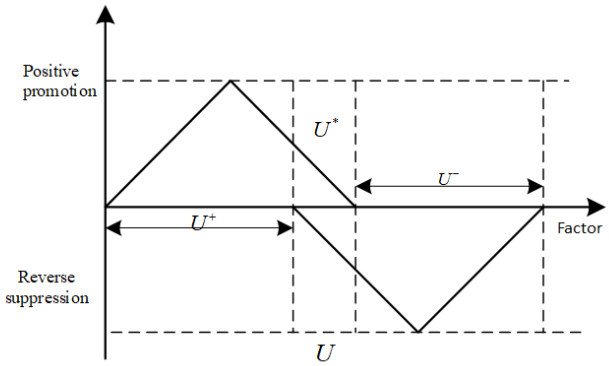

Fig. 1. The effect of impact factor

Therefore, the degree of positive promotion can be expressed by the fuzzy kiss degree $Q(x_i) \in (0,1]$. The closer the value of the kiss degree index is to 1, the more obvious the promotion effect of the factor. $Q(x_j) \in [-1,0)$ indicates the degree of reverse inhibition, and the closer the value of the kiss index is to -1, the more obvious the inhibition of the factor. When the direction of action of the factor is not clear and does not significantly affect the stability of the system, it is expressed by the degree of kiss $Q(x_k) = 0$. The relative membership matrix for the M state factors including the N factor indicators is expressed as formula (1).

$$R = \{r_{ij}\}_{n \times m} \quad (1)$$

Let the original index value of the factor set be O_i, the evaluation index value be $\overline{O_i}$, the minimum index value be α_i, and the maximum index value is β_i, then the fuzzy kissing function f can be defined as the formula (2).

$$f_i = \begin{cases} \dfrac{O_i - \overline{O_i}}{\overline{O_i} - \alpha_i}, O_i < \overline{O_i} \\ \dfrac{O_i - \overline{O_i}}{\overline{O_i} - \beta_i}, O_i > \overline{O_i} \end{cases} \quad (2)$$

In it, there exists $i = 1,2, \cdots, n$. According to the formula (1) relative membership matrix and formula (2) fuzzy kissing function, the kissing membership degree of each vulnerability factor is calculated, and the domain $U = U^+ \cup U^- \cup U^*$ is established. The factor set is decomposed into the promotion factor set U^+ and the suppression factor set U^-. The positive superiority vector R^+ and the negative superiority vector R^- of each factor affecting the system state can be established, which are represented as $R^+ = (r_1, r_2 \cdots, r_\alpha)^r$ and $R^- = (r_1, r_2 \cdots, r_\beta)^r$. Due to the nonlinear characteristics of the excitation and transmission process of urban mineral system vulnerability, a nonlinear mutation evaluation model needs to be established. In this paper, the Euclidean distance is used to represent the difference between the superiority vector R and various states. As shown in formula (3) (4).

$$I^+ = \sqrt{\sum_{i=1}^{\alpha} (\omega_i (g_i^+ - r_i))^2} \quad (3)$$

$$I^- = \sqrt{\sum_{j=1}^{\beta} (\omega_j (g_j^- - r_i))^2} \quad (4)$$

$g_i^+ = (g_1^+, g_1^+, \cdots g_a^+)^T = (1,1,\cdots,1)^T$ is the relative superiority vector of the factor indicator corresponding to the positive superior state, and ω_i, ω_j is represented as the weight vector. $g_j^- = (g_1^-, g_1^-, \cdots g_a^-)^T = (-1,-1,\cdots,-1)^T$ represents the relative superiority vector of the factor indicator corresponding to the reverse superior state. According to the literature (33), the concept of relative membership degree μ is introduced, and according to formula (3) and (4), the promotion membership degree μ^+ and the suppression membership degree μ^- are as defined by formula (5) and (6).

$$\mu^+ = \left[1 + \frac{\sum_{i=1}^{\alpha} (\omega_i (1 - r_i))^2}{\sum_{i=1}^{\alpha} (\omega_i r_i)^2}\right]^{-1} \quad (5)$$

$$\mu^- = \left[1 + \frac{\sum_{j=1}^{\beta} (\omega_j (1 - r_j))^2}{\sum_{j=1}^{\beta} (\omega_j r_j)^2}\right]^{-1} \quad (6)$$

Superimpose μ^+ and μ^-, construct membership degree μ, output vector $(\mu^+, \mu^-, \lambda_1\mu^+ + \lambda_2\mu^-)$, λ_1, λ_2 as weight parameter, which can be set and adjusted according to the actual application. According to the two-branch fuzzy function model constructed above, the relative membership degree μ^+ and the suppression relative membership degree μ^- of each vulnerability factor are calculated more accurately, and the range of index selection is expanded.

Therefore, the evaluation metrics can be considered more comprehensively, and the limitation of the underlying data weight of the catastrophe progression method is solved.

Risk Assessment and Early Warning Model Design

When using the catastrophe progression method to perform index decomposition and comprehensive evaluation analysis on the system, the target problem is first decomposed, and the target is gradually decomposed downward to obtain the measurable underlying index (The number of measurable indicators depends on the mutation model to be selected. Generally, the number of underlying measurement indicators is less than or equal to 4), the specific calculation model and steps are as follows.

Both-branch fuzzy mutation series modeling process:

1) Construct a multi-level evaluation index system (see **Table 1**): in order to facilitate the use of the mutation model in **Table 2**, the number of underlying measurement indicators is less than or equal to four, and the indicators of each layer of the urban mineral system vulnerability are described according to the second section.

2) Select the elementary mutation model: According to the potential function and the number of control variables, the apical mutation, the dovetail mutation and the butterfly mutation are applied in this paper. The basic structure of the model is shown in **Fig. 4**.

3) Establish the factor set U and the evaluation set V of the vulnerability relationship and establish a fuzzy kissing function. The forward index, the negative index and the two-way index $Q(x)$ are designed according to Section 3.2, and the relative membership matrix $R = (r_{ij})$ is calculated.

4) According to the index classification of step (3), the index set is decomposed into the promotion factor, the inhibition factor and the two-way factor on the domain $U = U^+ \cup U^- \cup U^*$, and the relative membership matrix $R^+ = (r_i)$ and $R^- = (r_j)$ are established.

5) According to formula (5) and (6), the upper-both branch fuzzy promotion membership degree μ^+ and the lower-both branch fuzzy suppression membership degree μ^- are obtained, and the membership degree value μ of the comprehensive state of each factor is obtained.

6) Data standardization processing: because the dimension and unit of the evaluation index are

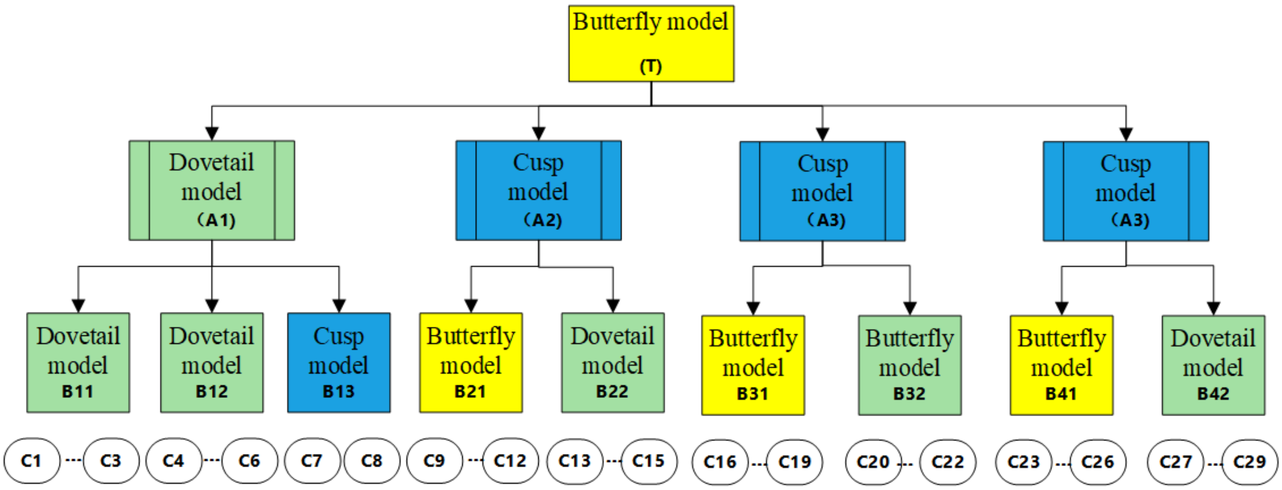

Fig. 2. The model of catasstrople evaluation

different, the effect is positive and negative, so the standard deviation method is used to deal with the index data without dimension, and the value of the [0~1] interval is taken.

7) Total mutation membership function calculation: after normalization, two different criteria are used to measure the effect of control variables on state variables. (1) Complementation criteria. Each control variable can make up for its deficiency and choose it according to its mean. (2) Non-complementation criteria. The control variables of a system cannot be substituted for each other and we take the value according to the principle of "taking small from big".

8) In such a layer-by-layer hierarchical operation, the state and control variables have a value range of [0, 1], and both belong to the larger the better, and the total mutation membership function value, that is, the system vulnerability risk level, can be obtained.

Thus, according to the fragility factor structure diagram of **Fig. 1**, we can establish the catastrophe progression evaluation index model shown in **Fig. 3**, which respectively shows the mutated model structure used by each brittle factor. Since the value of the total membership function obtained by the catastrophe progression method is in the range [0, 1], the risk warning can be divided into five levels according to the vulnerability characteristics and the scope of influence, which are respectively expressed as: high risk: 0.8~1.0; moderate risk: 0.6~0.8; low risk: 0.5~0.6; good: 0.4~0.5; healthy: 0.2~0.4. According to the evaluation of the catastrophe progression model, the risk warning level can be used to roughly determine the status of industrial development at a certain stage.

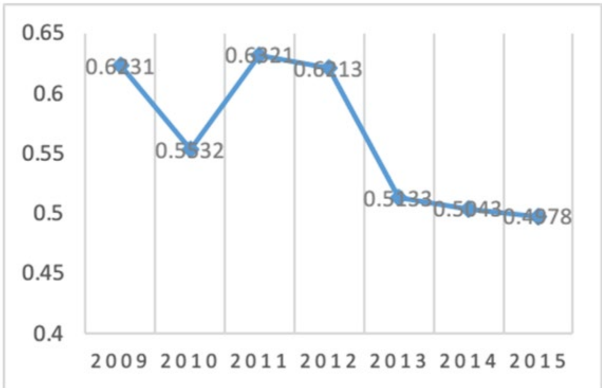

Fig. 3. Hunan Miluo Urban mineral vulnerability risk trends

EMPIRICAL ANALYSIS

Risk Assessment of Mineral Industry Vulnerability in Miluo City, Hunan Province

In 2010, Hunan Luolu Circular Economy Industrial Park became one of the first seven demonstration bases of "Urban Minerals" in China. By the end of the 12th Five-Year Plan, the base had more than 490 enterprises including agglomerate flow, recycling and processing, and the industrial chain continued to expand, forming a cluster of five renewable resources of recycled copper, aluminum, steel, plastic and rubber. The annual recycling capacity of renewable resources is 4 million tons, the processing volume has exceeded 2.4 million tons, and the annual output value is 30 billion yuan. The industrial agglomeration of the demonstration base has been accelerating, and the secondary pollution of the environment in the industrial system and the symbiotic

Table 4. The index data after standardization process (2009-2015)

Subsystem	index	2009	2010	2011	2012	2013	2014	2015
A1	C1	0.78	0.81	0.63	0.93	0.90	0.89	0.90
	C2	0.32	0.71	0.42	0.44	0.53	0.46	0.54
	C3	0.79	0.33	0.61	0.53	0.43	0.81	0.89
	C4	0.76	0.79	0.78	0.81	0.79	0.76	0.83
	C5	0.43	0.34	0.37	0.43	0.48	0.46	0.52
	C6	0.79	0.79	0.81	0.87	0.85	0.89	0.89
	C7	0.11	0.17	0.09	0.27	0.21	0.30	0.31
	C8	0.66	0.66	0.60	0.71	0.73	0.73	0.72
A2	C9	0.27	0.37	0.41	0.38	0.41	0.41	0.43
	C10	0.86	0.53	0.81	0.79	0.77	0.79	0.83
	C11	0.10	0.09	0.18	0.30	0.41	0.43	0.49
	C12	0.48	0.49	0.49	0.59	0.58	0.60	0.69
	C13	0.42	0.57	0.61	0.67	0.64	0.59	0.64
	C14	0.24	0.31	0.35	0.41	0.31	0.38	0.41
	C15	0.31	0.31	0.47	0.48	0.41	0.39	0.50
A3	C16	0.55	0.57	0.55	0.58	0.74	0.79	0.84
	C17	0.68	0.56	0.75	0.75	0.73	0.83	0.79
	C18	0.45	0.54	0.49	0.53	0.59	0.62	0.66
	C19	0.32	0.41	0.44	0.53	0.58	0.51	0.59
	C20	0.23	0.21	0.25	0.31	0.34	0.41	0.39
	C21	0.43	0.39	0.45	0.51	0.53	0.57	0.57
	C22	0.62	0.65	0.64	0.79	0.78	0.84	0.84
A4	C23	0.45	0.50	0.54	0.55	0.53	0.58	0.59
	C24	0.33	0.43	0.34	0.53	0.53	0.49	0.49
	C25	0.86	0.89	0.90	0.93	0.93	0.92	0.94
	C26	0.74	0.67	0.73	0.79	0.89	1.00	1.00
	C27	0.74	0.87	0.87	0.89	0.92	0.92	0.92
	C28	0.40	0.42	0.53	0.44	0.53	0.59	0.59
	C29	0.75	0.75	0.73	0.70	0.68	0.65	0.64

stability of its source supply, recycling, resource processing, market consumption, and management innovation have become increasingly prominent.

Data source and processing

Due to the late start of China's "urban minerals" industry, most of them have been transformed and upgraded from the renewable resources industry, which has limitations and lacks in the measurement and time of data statistics. The basic data we selected are from 2009-2015 "China Statistical Yearbook", "China Labor Statistics Yearbook", "Hunan Province Renewable Resources Industry Development Research Report", "Hunan Statistical Yearbook" and Hunan Miluo City Mineral Industrial Park Survey Data. There are some missing interruptions in the statistical data. In order to ensure the continuity of the indicators in time, the sample data is consistently processed, the sample data time continuity processing and the data normalization processing. The results are shown in **Table 4**.

Analysis of results

Before the establishment of the two-branch fuzzy mutation evaluation model, we convert the original data, establish a [0, 1] matrix, and calculate the Rij matrix from the index data according to the modeling process and formula (1) of **Table 3**. Then the fuzzy membership degree of each index is calculated, the fuzzy membership function is established, and the

Table 5. Urban mining subsystems relative membership degree (2009-2015)

	2009	2010	2011	2012	2013	2014	2015
Supply subsystem	0.2109	0.1976	0.1945	0.1987	0.1987	0.2019	0.2010
Recycling subsystem	0.1939	0.1874	0.1833	0.1863	0.1876	0.1765	0.1716
Reproduction subsystem	0.2333	0.2187	0.2210	0.2192	0.2588	0.2233	0.2287
Marketization subsystem	0.1930	0.1933	0.1925	0.1887	0.1992	0.2022	0.2120

Table 6. Urban mining subsystems vulnerability index (2009-2015)

	2009	2010	2011	2012	2013	2014	2015
Supply subsystem	0.8421	0.7011	0.7482	0.7321	0.7010	0.6423	0.6033
Recycling subsystem	0.6983	0.6185	0.6466	0.6732	0.6190	0.6140	0.6110
Reproduction subsystem	0.5210	0.4682	0.4666	0.4521	0.4193	0.4198	0.4103
Marketization subsystem	0.5990	0.5203	0.5833	0.5782	0.5644	0.5639	0.5344
Comprehensive index value	0.6231	0.5532	0.6321	0.6213	0.5133	0.5043	0.4978

domain U is established according to the matrix Rij,. Apply the formulas (5) and (6) to calculate the fuzzy relative membership degrees μ^+ and μ^- of the four subsystems. In this example, the weight coefficient $\lambda_1 = \lambda_2 = 1$, in view of the space, this paper directly gives the relative membership degree of the four subsystems of the Hunan Minlu City Mineral Demonstration Base between 2009 and 2015 (see **Table 5**). Finally, according to the different mutation subsystem types in the mutated series model structure of **Fig. 4**, the catastrophic series method is used to calculate the lateral comparison of the brittleness index of each subsystem for 7 years (such as **Table 6**) and the comprehensive brittleness index trend (**Fig. 4**).

It can be seen from **Table 5** that the vulnerability risk index values are all positive values in the four subsystems, which show that each brittleness factor can promote the system brittleness, and it is easy to be affected by internal and external factors, leading to brittle propagation, which causes the industrial chain to lose stability. Vulnerability analysis of different subsystems shows that in 2010, the vulnerability relationship of each subsystem is: supply system > recycling system > marketing system > reproduction system. It indicates that the supply chain has the greatest impact on system stability in the current year, and the reproduction subsystem has the least impact. By 2015, the brittleness warning value of the recycling subsystem is greater than the supply subsystem, and the brittleness warning value of the remanufacturing system is still the smallest. It shows that due to the imbalance of economic and educational development, the public's

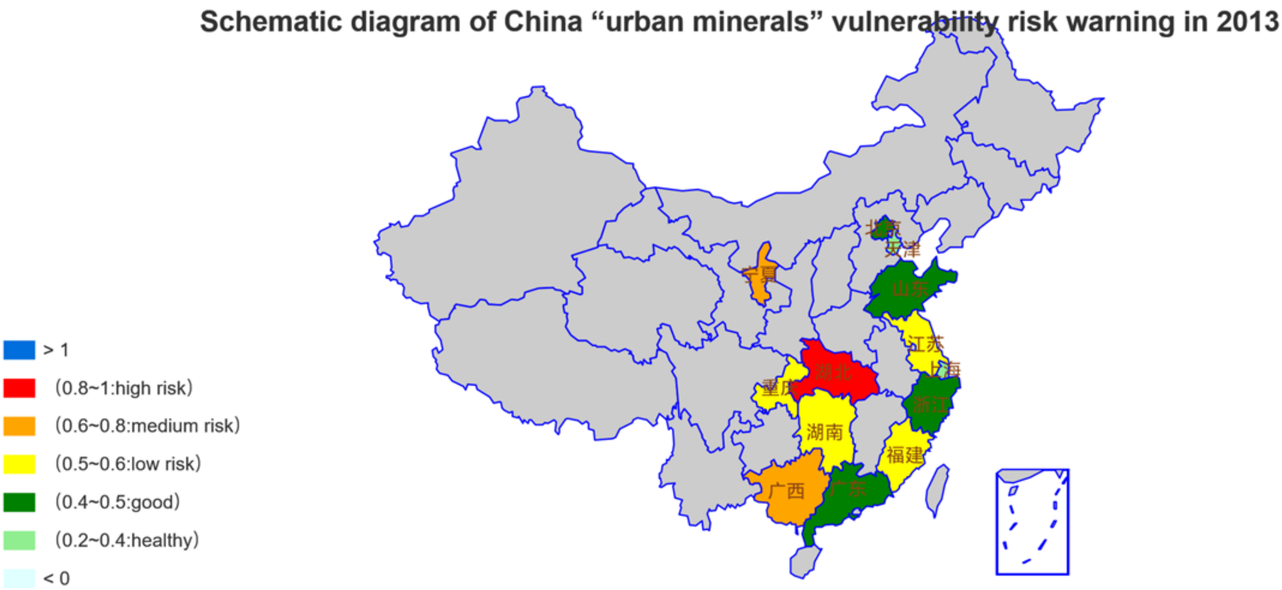

Fig. 5. Chinese 13 Urban mining bases vulnerability risk in 2013

awareness of recycling is still weak, the recycling system and network construction are not perfect, and the recycling subsystem and supply subsystem are easily affected by internal and external factors and cause instability. However, due to the guidance of the government, the company's technical input and capital investment are relatively sufficient, and the re-production subsystems in the industrial chain have strong capabilities, and its anti-risk ability is strong. The four subsystems constitute the cusp mutation complementary type and the dovetail mutation complement type. According to the catastrophe progression method, the precautionary value of the vulnerability risk of the entire Minnan urban mineral system in 2009-2015 can be obtained. It can be concluded from **Fig. 5** that after 2012, the development of the mineral industry in Miluo City has generally stabilized, and the overall risk factor has shown a downward trend. Among them, the first batch of the Jurassic Circular Economy Industrial Park in 2010 was established as a national urban minerals demonstration base, and the industrial restructuring has led to an increase in the industrial agglomeration process. In 2011 and 2012, the early warning value of industrial vulnerability risk rose by more than 0.6, reaching a medium risk value. It mainly reflects the unsuccessful adjustment of industrial structure after the upgrade of the demonstration base, coupled with the promulgation of new national and local policies, the lag of the management and implementation efficiency of the park, and the transmission of vulnerability risks caused by internal and external factors. However, the precautionary value of vulnerability risk declined sharply in 2013-2015 and reached a steady state. It is indicated that after the industrial agglomeration period, the industrial chain is continuously improved, and the development of the four subsystems in the industry tends to be balanced, and the entire industrial system can maintain good development.

Comparison of Vulnerability Risk of Mineral Industry in Different Regions

Because China has set up 6 batches of 49 mineral demonstration bases in 2010-2015 years, the data statistics cycle is difficult to be unified. Therefore, we selected the first 3 batches of the main 13 "urban mineral" demonstration bases in the 2013 panel data for horizontal comparison. This method is used to calculate the early warning value of vulnerability risk of 13 demonstration bases in the process of industrial agglomeration. The result is shown in **Fig. 5**. Only Tianjin Ziya and Shanghai Yanlongji have reached the "health" level (0.2-0.4); The "good" level (0.4-0.5) includes the four cities of Guangdong Qingyuan, Zhejiang Tonglu, Shandong Jinsheng and Beijing Lveng. The bases of Hunan Miluo, Chongqing Yongchuan, Fujian Huaying, and Jiangsu Zhangzhou are at the "low risk" level (0.5-0.6); The two bases in Wuzhou, Guangxi and Lingwu, Ningxia are "medium risk" warnings (0.6-0.8). Hubei Gucheng Base has reached a "high risk" warning.

(1) From the perspective of time period, in the first and second batch of urban mineral demonstration bases established in 2010, such as Tianjin Ziya, Guangdong Qingyuan, Shanghai

Yanlongji, Zhejiang Tonglu, Shandong Jinsheng and other urban minerals, they started earlier. Most of them are developed from the original recycling cycle resource industrial park, with long-term development and accumulation, the industrial cluster network is mature, the scale is large, and the supporting facilities are relatively perfect. At the same time, due to the wider market coverage and product coverage, the Hunan Minlu City Minerals Demonstration Base, which was developed in the same period, is healthier and more stable.

(2) From the perspective of economic geographical distribution, the overall level of urban mineral development in coastal areas is higher than that in central and inland areas. In particular, Tianjin Ziya, Shanghai Yanlongji and Guangdong Qingyuan Base, relying on the development of Binhai New Area, Yangtze River Delta and Pearl River Delta, have sufficient geographical advantages and resource advantages in the supply and recycling sectors. At the same time, Tianjin Ziya established the "China Renewable Resources Industry Technology Innovation Strategic Alliance" based on its educational and technological advantages. Guangdong Qingyuan established the "Qingyuan Recycling Metal Engineering R&D Center" and supporting financial institutions and research institutes. Therefore, it is also superior to other development bases in terms of talent and technology. The inland Ningxia and Guangxi urban mining bases are at medium risk level, mainly due to the low vulnerability assessment index of the marketization subsystem and supply subsystem. The vulnerability of these two links increases the vulnerability risk of the overall system.

(3) From the development trend, the development trend of Chongqing Yongchuan and Hunan Minlu in the central and western regions is relatively stable. Through the strong support of the government and the development of industrial agglomeration in recent years, the government has introduced leading enterprises through investment promotion, eliminated traditional small workshops, optimized and upgraded the layout of the park enterprises, and gradually developed into a modern production mode of scale, specialization and automation, so as to promote the development of enterprise entities and have a good development momentum in resource output rate and production efficiency. More surprisingly, Hubei Gucheng is the only "high risk" warning in the vulnerability risk warning. The Gucheng base is located in the center of the central transportation hub, and has obvious advantages in the location of the ground. However, the Gucheng base belongs to the typical representative of "industry-pull type". The industrial development of the park is due to the large demand for raw materials by local enterprises, and the formation and reuse of urban minerals is formed continuously, thus forming an urban mineral industrial base that interacts with local industries. It is extremely sensitive to the linkage effect of local upstream and downstream industries. Due to the transitivity of the vulnerability risk, its evaluation is weak in its ability to resist risks.

CONCLUSIONS

With the rapid advancement of China's new urbanization construction, resource constraints and environmental governance issues have become increasingly prominent. Accelerating the development and utilization of "urban minerals" and carrying out research on its industrial system vulnerability prevention and countermeasures are important contents for developing circular economy, cultivating strategic emerging industries, and building ecological civilization. This paper analyzes the network structure of the upper, middle and lower reaches of China's "urban minerals" from the perspective of socialization, and analyzes the causes of the fragility of China's "urban minerals" industrial system from the aspects of "supply, recycling, reproduction and marketization". We use the both-branch fuzzy mutation series method to construct the system vulnerability assessment system and establish a brittle risk early warning mechanism. We consider the redundancy and overlap of brittleness factors in all aspects of the industry, and use rough set theory to identify, reduce and correct the brittleness factors, and establish the order of importance of each index. We use the control variables and state variables of the catastrophe progression to describe the qualitative and catastrophic processes of key factors and indicators. Then we extend the membership function of the mutated series to the fuzzy kissing function by combining the two-branch fuzzy set, which expands the space of numerical selection, so that the metric of the evaluation index can be considered more comprehensively and objectively, and the risk early warning model can reflect the vulnerability factor to the system risk. The promotion and inhibition of the evolution process provides a new theoretical basis and analytical tool for revealing the development law of the industry. Finally, two empirical studies verify the effectiveness of the proposed method and draw relevant conclusions. Empirical Study 1: Through the horizontal data analysis of the development of the Yanluo City Minerals Demonstration Base in Hunan Province from 2009 to 2015, the results show that the four subsystems of the "Urban Minerals" vulnerability risk indicators have positive effects on the system fragility and are vulnerable to internal and external factors. In the two years after the upgrade of the demonstration base in 2010, the precautionary value of the vulnerability risk was greater than 0.6, reaching medium risk. However, with the extension of industrial agglomeration and the continuous improvement of the industrial chain, the precautionary value of vulnerability risk has dropped significantly in 2013-2015. The risk warning value in 2015 is less than 0.5, and the entire industrial system can maintain good development. Empirical Study 2: Select 13 national mineral demonstration bases in 2013 to conduct a comparative study on industrial vulnerability risk. The empirical results show that among the selected industrial system vulnerability factor structure, economic scale, economic geography, enterprise scale and industrial maturity have a great impact on industrial stability. More enterprises can be introduced through industrial agglomeration. The more large-scale enterprises with large industrial output value, the larger the enterprise scale and the higher the technology intensity, the more the upstream and downstream development of the industrial chain can be driven. The scale effect of leading enterprises drives the development of small and medium-sized enterprises, and promotes the overall technology investment, education and training, and market promotion in the four links of the industrial chain, reducing R&D investment risks and financing constraints. At the same time, most of the urban mineral industry is developed from the local original renewable resource industry. The threshold for entry is low, and it is still in the initial stage of development. At the initial stage of development, there is no significant feature in terms of recycling technology and profitability. However, for the medium and long-term development, the development of the technical level and the quality of the employees employed and the improvement of the management level of the enterprise will promote the mitigation of industrial vulnerability risks. Finally, when the government supports become more perfect, the resource endowment is more abundant, the manufacturing development level is higher, and the logistics capacity is more developed, the risk of industrial fragility is smaller. In the initial stage of industrial agglomeration, policy support factors have played a significant role. However, after several years of development, the industrial cluster has a fixed series of related enterprises upstream and downstream, thus forming a relatively independent development. Therefore, industrial stability will be affected by policy support at the beginning, but will begin to decrease later.

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