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Risk evaluation method based on set pair analysis applied to overseas mining investment

Introduction

To alleviate the bottleneck of resources for economic and social development, China's large-scale and competitive enterprises have gradually explored and developed overseas mineral resources to ensure a long-term and stable supply of resources (Armstrong et al. 2016). By the end of 2016, 1516 overseas enterprises operated in the mining sector, and the outward FDI stock flowing to the mining industry was $152.37 billion (Ministry of Commerce of the People's Republic of China et al. 2017). Given regional and cultural differences, overseas mining investment is generally faced with considerable risk from all aspects of the operation and is typically characterized as a large investment with long cycles faced with irreversibility and great uncertainty (Ke et al. 2012; Tang et al. 2017). To make better use of overseas mineral resources and obtain ideal social and economic benefits, enterprises must comprehensively evaluate the investment risks that are inherent in overseas mining investment.

Recently, following the advent of the multi-index evaluation, relevant knowledge from other fields has been used to enrich the current comprehensive evaluation methods. In addition to traditional methods, such as AHP (Sobczyk et al. 2017), fuzzy comprehensive evaluation (Eboli et al. 2016) and grey theory (Memon et al. 2015), the TOPSIS method, data

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envelopment analysis, attribute interval evaluation, particle swarm algorithm, BP neural network and other methods are gradually being applied (Kusi-Sarpong et al. 2015; Boloori 2016; Li et al. 2016b; Zhang et al. 2016; Shahabinejad and Sohrabpour 2017).

These comprehensive evaluation methods are also used in mining risk evaluation. Krystian Pera studied the application of the VaR concept in the risk assessment of a mineral investment project (Pera 2008); Wang Yong et al. constructed a risk assessment model for mining investment projects based on fuzzy neural network which is from the combination of fuzzy theory and neural networks (Wang and Yang 2010); Iloiu Mirela et al. argued the viability of the fuzzy sets' theory used in the mining project risk evaluation (Iloiu et al. 2013); Basiri M.H. et al. proposed a Fuzzy Synthetic Evaluation (FSE) approach as a new tool for ranking the risks in mining projects (Basiri and Azad 2015); Li Hui et al. proposed a qualitative-quantitative comprehensive risk evaluation method combining the fuzzy mathematics and the grey system theory to analyze the investment risks of one Chinese overseas oil refining project as a case study (Li et al. 2017). In addition, Wang Zuogong (Wang et al. 2013), Wang Xunhong, Dong Longjun (Dong et al. 2017) and Ruan Jinghua (Jinghua et al. 2018) et al. have also done relevant researches.

However, due to the complicated risk factors, incomplete quantitative indexes and the uncertainty of overseas mining investment, the above methods may be suboptimal for achieving the desired evaluation results. To fully consider the impact of uncertainty during a risk assessment, the set pair analysis (SPA) theory can be used to evaluate overseas mining investment risk.

Zhao (Zhao 1989) proposed the SPA theory, which is a systematic theory and method to address uncertainty that has been applied in many fields. Qiang Zou et al. (Zou et al. 2013) proposed a new model for comprehensive flood risk assessment based on SPA and the variable fuzzy sets (VFS) theories; Jin Tao et al. (Tao et al. 2014) presented a multifunctional indicator system for the performance evaluation of a crop production system using the SPA method; Mingwu Wang et al. (Wang et al. 2014) introduced a dynamic SPA method based on variable weights to assess liquefaction; and Chunhui Li et al. (Li et al. 2016a) established an integrated model based on k-means clustering analysis and SPA for evaluating the risks associated with water pollution in source water areas. SPA theory uniformly treats certainty and uncertainty as one identity-discrepancy-contrary system and is superior for solving uncertainty problems during an evaluation (Ren et al. 2013; Guo et al. 2014; Wei et al. 2016; Pan et al. 2017); however, it has not yet been applied to assess overseas mining investment risk.

Therefore, based on an analysis of the risk factors of overseas mining investment, a risk evaluation index system was constructed, and based on SPA theory, a 5-element connection number model of risk evaluation was established. Overseas mining investment risk and its changing trends were synthetically evaluated by calculating the adjacent connection number and analyzing the set pair potential. In addition, the practicability and effectiveness of the evaluation method were illustrated using an overseas mining investment project as an example.

1. Theoretical Framework

The SPA theory is a systematic theory and method that addresses the uncertainty caused by fuzzy, random and incomplete information by using a connection number. It can recognize objective uncertainty and uniformly treats both uncertainty and certainty as an identity-discrepancy-contrary system for dialectical analysis and mathematical processing (Zhao 2000).

1.1. Set pair and connection number

A set pair is a pair that comprises two sets with a certain relationship and is the basic unit of set pair analysis (Feng et al. 2014). It is stipulated in mathematics that the elements of a set can be people, matter, objects, numbers, concepts, etc. Thus, a teacher and a student, investment and return, quality and standards, methods and objects, past and present, and certainty and uncertainty, for example, can all be treated as set pairs in a given context. With respect to a given problem Q, a set pair H is formed by putting two interrelated sets S_1 and S_2 together.

A connection degree is an important concept for SPA theory and represents the degree of similarities and differences between two interrelated sets that form a set pair. Under the given problem Q, the T features of set pair H consisting of sets S_1 and S_2 are analyzed. If there are T_1 features that are common to sets S_1 and S_2, T_2 features that are opposite, and T_3 features that are neither common nor opposite, then the connection degree of the set pair H is generally expressed as follows (Zhao 1989):

$$\mu = \frac{T_1}{T} + \frac{T_3}{T} i + \frac{T_2}{T} j \tag{1}$$

where μ represents the “identity”–“discrepancy”–“contrary” connection degree of set pair H for problem Q; T is the total number of features; T_1 represents the identical features; T_2 represents the contrary features and $T_3 = T - T_1 - T_2$ represents the discrepancy features of the two sets.

T_1/T, T_3/T and T_2/T represent the identity, discrepancy and contrary degrees of the set pair under a certain condition, respectively. By defining $a = T_1/T$, $b = T_3/T$, and $c = T_2/T$, formula (1) can be rewritten as:

$$\mu = a + bi + cj \tag{2}$$

In this formula, a, b, and c are connection components, and satisfy the normalized condition $a + b + c = 1$. a, b, and c are any real numbers between 0 and 1, which can be described as $a, b, c, \in [0,1]$. i is the discrepancy coefficient, and $-1 \leq i \leq 1$; j is the contrary coefficient, and $j = -1$. In the analysis, formula (2) may also be referred to as the connection number.

The connection number, which links the identity, discrepancy, and contrary of a set pair, describes a certain–uncertain system. In formula (2), *a* and *cj* reflect the certainty of the system, and *bi* reflects the uncertainty of the system.

The adjacent connection number, which can be derived from the system hierarchy of the connection components, is a companion function of the connection number. It reveals the obvious development trend of any two adjacent connection components in the connection number and can predict the future of the current state (Yue et al. 2014; Zhao and Zhao 2014). According to the definition, positive and negative adjacent connection numbers respectively indicate the magnitudes of the left and right pulling effects of the connection component on the adjacent connection component in the connection number.

Using the connection number in formula (2) as an example, the positive adjacent connection number is as follows:

$$\mu_{AD}^{+} = \frac{a}{b} + \frac{b}{c} i^{+} \tag{3}$$

The negative adjacent connection number is as follows:

$$\mu_{AD}^{-} = \frac{b}{a} i^{-} + \frac{c}{b} j^{-} \tag{4}$$

The full adjacent connection number is as follows:

$$\mu_{AD} = \mu_{AD}^{+} + \mu_{AD}^{-} \tag{5}$$

The full adjacent connection number can comprehensively reflect the potential trends of the system. According to the rules, $\mu_{AD} > 1$ indicates that the system has a potential positive trend, while $\mu_{AD} < 1$ indicates that the system has a potential negative trend, and $\mu_{AD} = 1$ represents a critical trend.

1.2. Set pair potential and identity-discrepancy-contrary analysis

In the SPA theory, when $c \neq 0$ in formula (2), the concept of set pair potential (*SPP*) is defined as the ratio of the identity degree "a" and the contrary degree "c" (Hu and Yang 2011; Kan et al. 2012), which can be recorded as:

$$SPP = \frac{a}{c} \tag{6}$$

The set pair potential is the comparison of the relative size of the identity, discrepancy and contrary in the context of a specified problem, and in a certain sense, it reflects the dynamic evolution trend of the two sets. In formula (6), if $a/c > 1$, then we refer to *SPP* as the identity potential, which means the two sets in the set pair have an identical tendency. If $a/c = 1$, then we refer to *SPP* as the balance potential, which means the two sets are in an "evenly matched" state. If $a/c < 1$, then we refer to *SPP* as the contrary potential, which means the two sets have contrary tendencies. It should be noted that the actual meanings of "identical tendency" and "contrary tendencies" here should be understood in light of the corresponding problem background and the pre-given reference set.

We can further identify strong, quasi, weak and micro identity potentials according to the *b* value, corresponding to the four cases $a > c > b$, $a > c$ and $b = 0$, $a > b > c$, and $b > a > c$, respectively. Similarly, the balance and contrary potentials can also be further identified according to the b value; to clarify, the strength order of the set pair potential can be sorted by the coefficients to obtain the corresponding set pair potential sequence (Chong et al. 2017).

2. Methods and procedures

Formula (2) is referred to as the 3-element connection number, which represents the general form. However, in practice, the two sets may have more than one type of discrepancy degree. In this situation, we can further generalize bi to $b_1i_1 + b_2i_2 + \ldots b_{n-2}i_{n-2}$, and then obtain the multi-element connection number, which can increase the connection component, reduce the value range of each component coefficient and thereby weaken the impact of uncertainty. The multi-element connection number is given by formula (7):

$$\mu = a + b_1i_1 + b_2i_2 + \ldots + b_{n-2}i_{n-2} + cj \tag{7}$$

When $n = 5$, the 5-element connection number can be obtained as:

$$\mu = a + b_1i_1 + b_2i_2 + b_3i_3 + cj \tag{8}$$

To make it easier to write, the 5-element connection number is often written as follows (Hou et al. 2017):

$$\mu = a + bi + cj + dk + el \tag{9}$$

In this formula, *a, b, c, d* and *e* are connection components, which satisfies the normalized condition $a + b + c + d + e = 1$. *a, b, c, d* and *e* are any real numbers between 0 and 1,which can be described as $\forall\, a, b, c, d, e \in [0,1]$. *i, j* and *k* are the discrepancy coefficients, denoted as the different grades of discrepancy degree, and $-1 \leq i \leq 1$, $j \in [0,0]$ (the neutral mark does not imply that $j = 0$), $-1 \leq k \leq 0$. l is the contrary coefficient, and $l = -1$.

According to formulas (3) and (4), the positive and negative adjacent connection numbers of 5-element connection number are as follows:

$$\mu_{AD}^{+} = \frac{a}{b} + \frac{b}{c}i^{+} + \frac{c}{d}j^{+} + \frac{d}{e}k^{+} \tag{10}$$

$$\mu_{AD}^{-} = \frac{b}{a}i^{-} + \frac{c}{b}j^{-} + \frac{d}{c}k^{-} + \frac{e}{d}l^{-} \tag{11}$$

The 5-element connection number is suitable for describing a system that divides the study object into five different levels. For evaluating the risk of overseas mining investment, each component of the 5-element connection number can be mapped to a level of risk.

Based on SPA theory, the steps of the risk evaluation are as follows:

1. Analyze the risk factors of overseas mining investment and establish the risk evaluation index system. If there are n indexes in the index system, then the set of risk factors is $X = \{x_1, x_2, ..., x_n\}$.

2. Identify the levels of risk to be considered in the evaluation.

The existence of many qualitative indicators must be considered in the risk evaluation of overseas mining investment; these indicators are quantified by identifying the levels of risk. Investment risk is defined as an uncertain event or condition that, if it occurs, has a negative effect on an investment's objectives. According to the probability of occurrence, the risk is divided into five levels from low to high, which correspond to the 5-element connection number:

- Level I: There is no risk in the investment, that is, there is no event or condition that has a negative effect on the investment.
- Level II: There is low risk in the investment, which means that the occurrence probability of an event that has a negative effect is low.
- Level III: There is medium risk in the investment, which means that the occurrence probability of an event that has a negative effect is medium.
- Level IV: There is high risk in the investment which means that the occurrence probability of an event that has a negative effect is high.
- Level V: The events which have negative effects on the investment will surely occur.

3. Determine the weight of each risk factor in the index system.

The weight determination plays a key role in the SPA, given its crucial effect on the assessment results (Wang et al. 2015).

The entropy weight method is one of the objective weighting methods. It was firstly introduced from thermodynamics to information systems (Shannon 2001). In this study, since the concept of entropy is a measure of uncertainty in information formulated in terms of probability theory and is well suited for measuring the relative contrast intensities of criteria to represent the average intrinsic information, it is a proper option for our purposes (Shemshadi et al. 2011; Amiri et al. 2014).

The process of calculating the weights using the entropy weight method can be achieved through Matlab programming. The weight matrix is $W = \{w_1, w_2, ..., w_n\}$.

4. Establish the two basic sets for each risk factor. Set S_1 is an ideal reference set, that is, the factor is completely in a risk-free state, and set S_2 is the actual scoring result of the factor. These two basic sets form the set pair H for the risk analysis of factors.

In the context of risk assessment, the features of set pair H consisting of sets S_1 and S_2 are analyzed. T is the total number of features; T_1 is the number of features that are common to sets S_1 and S_2; T_2 is the number of features that are opposite; T_3^1 is the number of features that are discrepancy biased towards identity; T_3^2 is the number of features that are medium discrepancy; T_3^3 is the number of features that are discrepancy biased towards contrary.

Taking the risk factor x_n as an example, according to the definition of connection number, all features of the risk-free reference set S_1 are in Level I risk level, and for the actual scoring result set S_2, the specific meaning of each parameter is as follows:

- T is the total number of experts participating in scoring;
- T_1 is the number of experts who grade risk factor x_n as level I, that is, there are T_1 experts who consider that x_n has no risk and is the same as risk-free reference set S_1;
- T_2 is the number of experts who grade risk factor x_n as level V, that is, there are T_2 experts who consider that x_n will surely have a negative impact on investment;
- T_3^1 is the number of experts who grade risk factor x_n as level II, that is, there are T_3^1 experts who consider that the risk of x_n is low;
- T_3^2 is the number of experts who grade risk factor x_n as level III, that is, there are T_3^2 experts who consider that the risk of x_n is medium;
- T_3^3 is the number of experts who grade risk factor x_n as level IV, that is, there are T_3^3 experts who consider that the risk of x_n is high.

The 5-element connection number model for the risk factor x_n can be constructed as:

$$\mu_n = a_n + b_n i_1 + c_n j + d_n k + e_n l \tag{12}$$

where a_n, b_n, c_n, d_n, e_n are connection components of the risk factor x_n, whose values are scored by a number of experts for the risk level of the factor. Formula (12) shows that according to the theory of SPA, $a_n = \frac{T_1}{T}$, $b_n = \frac{T_3^1}{T}$, $c_n = \frac{T_3^2}{T}$, $d_n = \frac{T_3^3}{T}$, and $e_n = \frac{T_2}{T}$.

5. Construct the identity-discrepancy-contrary assessment model to evaluate the risk of overseas mining investment, as shown in formula (13).

$$\mu = (w_1, w_2, \ldots, w_n)\begin{pmatrix} a_1 & b_1 & c_1 & d_1 & e_1 \\ a_2 & b_2 & c_2 & d_2 & e_2 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_n & b_n & c_n & d_n & e_n \end{pmatrix}\begin{pmatrix} 1 \\ i \\ j \\ k \\ l \end{pmatrix} = \tag{13}$$

$$= \sum_{\lambda=1}^{n} w_\lambda a_\lambda + \sum_{\lambda=1}^{n} w_\lambda b_\lambda i + \sum_{\lambda=1}^{n} w_\lambda c_\lambda j + \sum_{\lambda=1}^{n} w_\lambda d_\lambda k + \sum_{\lambda=1}^{n} w_\lambda e_\lambda l$$

6. Analyze the evaluation results based on the set pair potential and the adjacent connection number.

The risk is divided into identity potential, balance potential and contrary potential based on the set pair potential of the 5-element connection number to measure the risk of the system. When risk exists in the identity potential, it means that set S_1 and set S_2 have an identical tendency; that is, the actual evaluation result is close to the risk-free state, so the risk is low. Similarly, when risk exists in the balance potential, the risk is in the middle state between high and low risk, which means we should pay close attention to the connection number and the adjacent connection number of each factor and improve the factors related to the contrary potential to move system risk to the identity potential. When risk has contrary potential, it means set S_1 and set S_2 have contrary tendencies, so the risk is in a high state, which means we should focus on all the factors related to the contrary potential to move the system risk to the balance potential and, ultimately, to the identity potential.

Next, the full adjacent connection number of each risk factor and the overall system must be calculated to determine future risk trends. $\mu_{AD} > 1$ indicates that the risk has a downward trend, while $\mu_{AD} < 1$ indicates that the risk has an upward trend and $\mu_{AD} = 1$ represents a critical trend.

3. Model construction

3.1. Risk analysis of overseas mining investment

The risk of overseas mining investment is classified according to the risk field. Risk can be separated into five categories: natural and geological risk, political and legal risk, economic and financial risk, social and environmental risk, and technical and management risk.

1. **Natural and geological risk** refers to the risk due to the natural and geological conditions of the investment area, such as the frequency and extent of natural disasters;

the scale, quality and distribution of geological resources; risks related to deposits hydrogeology, engineering and environmental geology; risks related to the exploration of resources, and issues related to the reliability of reserves.

2. **Political and legal risk** refers to the possibility that a loss will be incurred by an investment project or that income will deviate from the expected levels due to political changes in the host country, changes in political measures, or administrative and legal restrictions. Issues that affect political and legal risk include political stability, bilateral relations, mining investment policies, policy continuity and tax systems for mining (Misheelt Ganbold, Saleem H. Ali 2017).
3. **Economic and financial risk** refers to risk that arises due to long production cycles, large capital investment, exchange rate fluctuations, macroeconomic volatility or other issues. This type of risk can have a negative economic impact on mining projects and can be affected by metal prices, raw material prices, exchange rate fluctuations, financing channels, payback periods, the Internal Rate of Return (IRR), etc. (Achzet and Helbig 2013).
4. **Social and environmental risk** refers to risk that arises due to the considerable cultural differences of countries and regions, including religion and faith, habits, language, education, and management styles. This type of risk primarily affects the social and environmental benefits and relationships with the local community, which has an impact on the reputation of the enterprise and the smooth progress of the project. Socialand environmental risk is affected by factors such as social stability, labor costs, trade unions and labor disputes, cultural inclusiveness, religious and cultural differences, environmental regulatory constraints and infrastructure construction (Tang-Lee 2016).
5. **Technical and management risk** refers to risk caused by the limitations of the technical management of the mining project during the entire process of exploration and development. Issues that affect this risk include the adaptability of the mining method, mining conditions, the degree of difficulty of the mining and smelting processes, and the cross-cultural experience of management.

3.2. Construction of the risk evaluation index system and determination of weight

Based on an analysis of the risk factors of overseas mining investment, the risk assessment is taken as a target layer, the five categories of risk are taken as criterion layer, and specific risk factors are taken as index layer. The risk evaluation index system is constructed as shown in Figure 1.

The China Nonferrous Metals Group Co., Ltd. invested in a copper mine in Zambia, which will be used as an example. The risk factors of the project were evaluated by issuing questionnaires to 20 industry experts, front-line employees and managers. According to the

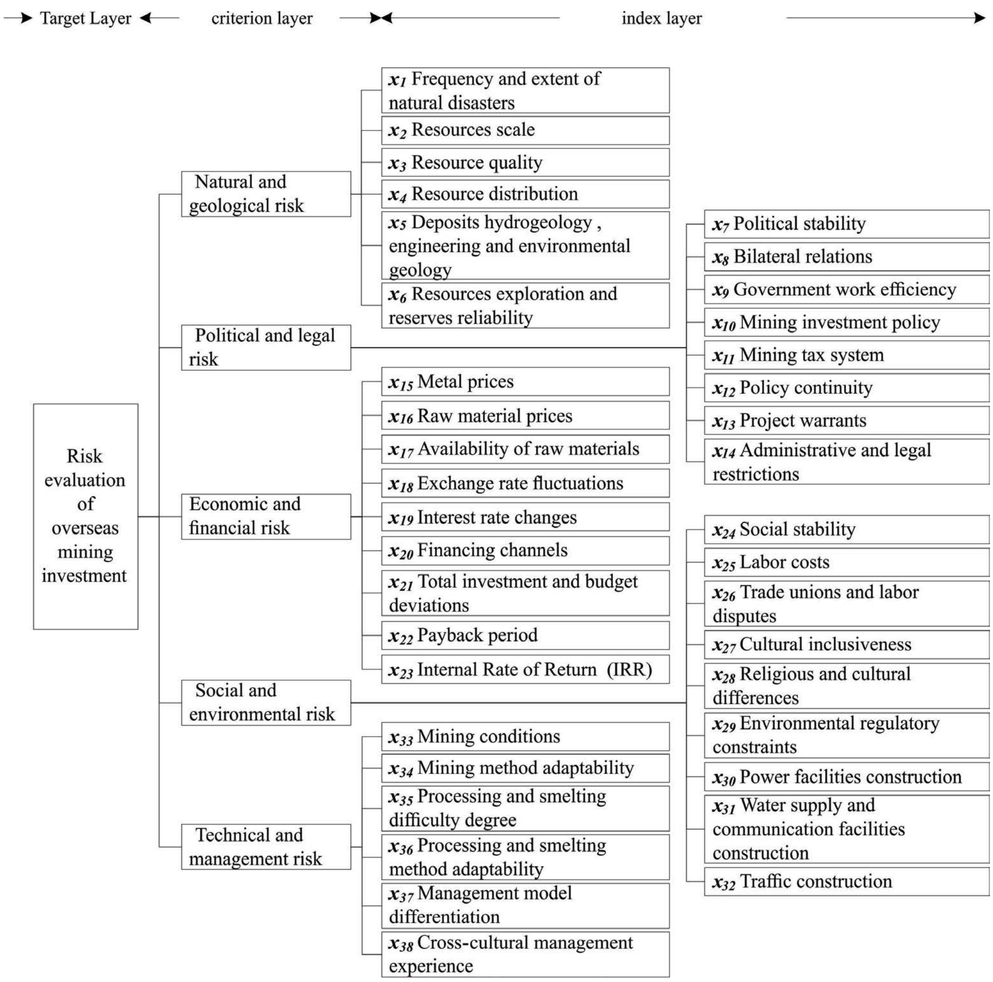

Fig. 1. Overseas mining investment risk evaluation index system

Rys. 1. Indeksy systemów oceny ryzyka zagranicznych inwestycji górniczych

results, the weight of each risk factor is calculated by the entropy weight method. The results are as follows:

$$W = (w_1, w_2, \ldots, w_{38})$$
$$= (0.022, 0.032, 0.032, 0.01, 0.055, 0.002, 0.023, 0.041, 0.018, 0.028, 0.028, 0.038, 0.031,$$
$$0.03, 0.02, 0.022, 0.032, 0.026, 0.041, 0.058, 0.041, 0.041, 0.021, 0.024, 0.014, 0.031,$$
$$0.025, 0.018, 0.013, 0.018, 0.022, 0.01, 0.028, 0.015, 0.027, 0.024, 0.018, 0.022)$$

3.3. Construction of the identity-discrepancy-contrary risk assessment model

According to formula (13), the identity-discrepancy-contrary risk assessment model of overseas mining investment is constructed as shown in Table 1.

Using risk factor x_1 in the index layer as an example, among the 20 experts participating in evaluation, the number of experts who scored Level I to Level V was 7, 6, 5, 1 and 1 respectively. Consequently, the identity degree component $a_1 = 0.35$, the discrepancy degree component biased towards identity $b_1 = 0.3$, the medium discrepancy degree component $c_1 = 0.25$, the discrepancy degree component biased towards contrary $d_1 = 0.05$, and the contrary degree component $e_1 = 0.05$. The 5-element connection number model of x_1 is:

$$\mu_1 = 0.35 + 0.3i + 0.25j + 0.05k + 0.05l$$

Then, the set pair potential is:

$$SPP_1 = \frac{\text{the identity degree component}}{\text{the contrary degree component}} = \frac{a_1}{e_1} = \frac{0.35}{0.05} = 7$$

As $SPP_1 > 1$, the set pair potential of this risk factor is the identity potential, which indicates low risk.

According to formula (10), the positive adjacent connection number of risk factor x_1 is as follows:

$$\mu_{AD_1}^{+} = \frac{a_1}{b_1} + \frac{b_1}{c_1} i^{+} + \frac{c_1}{d_1} j^{+} + \frac{d_1}{e_1} k^{+} = 1.17 + 1.2i^{+} + 5j^{+} + k^{+}$$

According to the proportional value method, the component coefficients of the positive adjacent connection number are calculated:

$$i^{+} = \frac{\frac{a_1}{b_1}}{\frac{a_1}{b_1} + \frac{b_1}{c_1}} n, \quad j^{+} = \frac{\frac{b_1}{c_1}}{\frac{b_1}{c_1} + \frac{c_1}{d_1}} n, \quad k^{+} = \frac{\frac{c_1}{d_1}}{\frac{c_1}{d_1} + \frac{d_1}{e_1}}$$

Then $\mu_{AD_1}^{+} = 1.17 + 1.2i^{+} + 5j^{+} + k^{+} = 3.56$.

Similarly, the negative adjacent connection number is:

$$\mu_{AD_1}^{-} = 0.86i^{-} + 0.83j^{-} + 0.2k^{-} + l^{-} = -0.25$$

Therefore, the full adjacent connection number of the risk factor x_1 is:

$$\mu_{AD_1} = \mu^+_{AD_1} + \mu^-_{AD_1} = 3.56 - 0.25 = 3.31$$

As $\mu_{AD_1} > 1$, it indicates that the risk factor has a potential trend towards positive change, that is, the risk has a downward trend.

Similarly, the set pair potential and the full adjacent connection number of other risk factors can be calculated. The results are shown in Table 1.

Table 1 Identity-discrepancy-contrary risk assessment model of overseas mining investment

Tabela 1. Model oceny ryzyka zagranicznych inwestycji z użyciem identyfikacji rozbieżności

Criterion layer	Index layer	Weight	5-element connection number model	Set pair potential	Full adjacent connection number
Natural and geological risk	x_1 Frequency and extent of natural disasters	0.022	$\mu_1 = 0.35 + 0.3i + 0.25j + 0.05k + 0.05l$	identity potential	3.31
	x_2 Resource scale	0.032	$\mu_2 = 0.45 + 0.35i + 0.1j + 0.05k + 0.05l$	identity potential	3.89
	x_3 Resource quality	0.032	$\mu_3 = 0.4 + 0.4i + 0.1j + 0.05k + 0.05l$	identity potential	3.50
	x_4 Resource distribution	0.010	$\mu_4 = 0.35 + 0.25i + 0.2j + 0.1k + 0.1l$	identity potential	3.51
	x_5 Deposits hydrogeology, engineering and environmental geology	0.055	$\mu_5 = 0.05 + 0.1i + 0.7j + 0.1k + 0.05l$	balance potential	3.61
	x_6 Resource exploration and reserves reliability	0.002	$\mu_6 = 0.15 + 0.25i + 0.15j + 0.25k + 0.2l$	**contrary potential**	2.51
Subtotal		0.154	$\mu = 0.27 + 0.26i + 0.34j + 0.07k + 0.06l$	identity potential	3.33
Political and legal risk	x_7 Political stability	0.023	$\mu_7 = 0.35 + 0.35i + 0.2j + 0.05k + 0.05l$	identity potential	3.39
	x_8 Bilateral relations	0.041	$\mu_8 = 0.6 + 0.2i + 0.1j + 0.05k + 0.05l$	identity potential	5.65
	x_9 Government work efficiency	0.018	$\mu_9 = 0.05 + 0.25i + 0.4j + 0.2k + 0.1l$	**contrary potential**	3.17
	x_{10} Mining investment policy	0.028	$\mu_{10} = 0.1 + 0.5i + 0.25j + 0.1k + 0.05l$	identity potential	3.00

Table 1 cont.

Tabela 1. cd.

Criterion layer	Index layer	Weight	5-element connection number model	Set pair potential	Full adjacent connection number
Political and legal risk	x_{11} Mining tax system	0.028	$\mu_{11} = 0.1 + 0.25i + 0.5j + 0.1k + 0.05l$	identity potential	3.44
	x_{12} Policy continuity	0.038	$\mu_{12} = 0.1 + 0.6i + 0.05j + 0.1k + 0.15l$	**contrary potential**	**0.62**
	x_{13} Project warrants	0.031	$\mu_{13} = 0.5 + 0.25i + 0.15j + 0.05k + 0.05l$	identity potential	4.47
	x_{14} Administrative and legal restrictions	0.030	$\mu_{14} = 0.15 + 0.1i + 0.55j + 0.05k + 0.15l$	balance potential	**–0.06**
Subtotal		0.237	$\mu = 0.27 + 0.32i + 0.25j + 0.08k + 0.08l$	identity potential	2.92
Economic and financial risk	x_{15} Metal prices	0.020	$\mu_{15} = 0.4 + 0.3i + 0.15j + 0.1k + 0.05l$	identity potential	4.22
	x_{16} Raw material prices	0.022	$\mu_{16} = 0.05 + 0.15i + 0.45j + 0.1k + 0.25l$	**contrary potential**	**0.59**
	x_{17} Availability of raw materials	0.032	$\mu_{17} = 0.05 + 0.4i + 0.4j + 0.1k + 0.05l$	balance potential	3.13
	x_{18} Exchange rate fluctuations	0.026	$\mu_{18} = 0.05 + 0.05i + 0.2j + 0.45k + 0.25l$	**contrary potential**	3.85
	x_{19} Interest rate changes	0.041	$\mu_{19} = 0.1 + 0.2i + 0.6j + 0.05k + 0.05l$	identity potential	2.31
	x_{20} Financing channels	0.058	$\mu_{20} = 0.7 + 0.15i + 0.05j + 0.05k + 0.05l$	identity potential	7.62
	x_{21} Total investment and budget deviations	0.041	$\mu_{21} = 0.6 + 0.2i + 0.1j + 0.05k + 0.05l$	identity potential	5.65
	x_{22} Payback period	0.041	$\mu_{22} = 0.05 + 0.1i + 0.6j + 0.05k + 0.2l$	**contrary potential**	–1.30
	x_{23} IRR (Internal Rate of Return)	0.021	$\mu_{23} = 0.3 + 0.3i + 0.3j + 0.05k + 0.05l$	identity potential	3.00
Subtotal		0.303	$\mu = 0.3 + 0.19i + 0.31j + 0.1k + 0.1l$	identity potential	3.13
Social and environ-mental risk	x_{24} Social stability	0.024	$\mu_{24} = 0.3 + 0.4i + 0.2j + 0.05k + 0.05l$	identity potential	3.16
	x_{25} Labour costs	0.014	$\mu_{25} = 0.25 + 0.15i + 0.1j + 0.1k + 0.4l$	**contrary potential**	**0.77**
	x_{26} Trade unions and labour disputes	0.031	$\mu_{26} = 0.05 + 0.05i + 0.15j + 0.5k + 0.25l$	**contrary potential**	3.93

Table 1 cont.

Tabela 1. cd.

Criterion layer	Index layer	Weight	5-element connection number model	Set pair potential	Full adjacent connection number
Social and environ-mental risk	x_{27} Cultural inclusiveness	0.025	$\mu_{27} = 0.5 + 0.15i + 0.2j + 0.1k + 0.05l$	identity potential	5.85
	x_{28} Religious and cultural differences	0.018	$\mu_{28} = 0.4 + 0.2i + 0.25j + 0.1k + 0.05l$	identity potential	4.67
	x_{29} Environmental regulatory constraints	0.013	$\mu_{29} = 0.35 + 0.2i + 0.25j + 0.15k + 0.05l$	identity potential	4.59
	x_{30} Power facilities construction	0.018	$\mu_{30} = 0.05 + 0.25i + 0.4j + 0.2k + 0.1l$	**contrary potential**	3.17
	x_{31} Water supply and communication facilities construction	0.022	$\mu_{31} = 0.3 + 0.25i + 0.35j + 0.05k + 0.05l$	identity potential	2.95
	x_{32} Traffic construction	0.010	$\mu_{32} = 0.2 + 0.3i + 0.3j + 0.1k + 0.1l$	identity potential	2.67
Subtotal		0.174	$\mu = 0.26 + 0.21i + 0.24j + 0.17k + 0.12l$	identity potential	3.59
Technical and management risk	x_{33} Mining conditions	0.028	$\mu_{33} = 0.05 + 0.25i + 0.5j + 0.1k + 0.1l$	**contrary potential**	2.41
	x_{34} Mining method adaptability	0.015	$\mu_{34} = 0.15 + 0.3i + 0.35j + 0.15k + 0.05l$	identity potential	3.66
	x_{35} Processing and smelting difficulty degree	0.027	$\mu_{35} = 0.4 + 0.35i + 0.15j + 0.05k + 0.05l$	identity potential	3.70
	x_{36} Processing and smelting method adaptability	0.024	$\mu_{36} = 0.4 + 0.2i + 0.3j + 0.05k + 0.05l$	identity potential	3.63
	x_{37} Management model differentiation	0.018	$\mu_{37} = 0.1 + 0.3i + 0.4j + 0.1k + 0.1l$	balance potential	2.33
	x_{38} Cross-cultural management experience	0.022	$\mu_{38} = 0.35 + 0.25i + 0.3j + 0.05k + 0.05l$	identity potential	3.25
Subtotal		0.133	$\mu = 0.25 + 0.27i + 0.33j + 0.08k + 0.07l$	identity potential	3.06
Total		1	$\mu = 0.27 + 0.25i + 0.29j + 0.1k + 0.09l$	identity potential	3.19

4. Analysis and discussion

4.1. Results analysis

According to the results in Table 1:

1. The overall 5-element connection number of overseas mining investment risk evaluation is $\mu = 0.27 + 0.25i + 0.29j + 0.1k + 0.09l$. The set pair potential is the identity potential, which indicates that the overall risk of the investment project is acceptable. In addition, the full adjacent connection number is 3.19>1, which indicates that the risk of the entire investment project has a downward trend.
2. Regarding the specific risk factors, 24 risk factors have an identity potential, 4 have a balance potential and 10 have a contrary potential, which indicates that among all the 38 risk factors, 24 have low risk, 4 are in the middle state between high risk and low risk, and 10 have a high risk. Meanwhile, for 33 risk factors, the risk has a downward trend, and for 5 risk factors, the risk has an upward trend.

Table 2 Analysis of high risk factors based on field investigation

Tabela 2. Przykładowa analiza czynników wysokiego ryzyka

Risk Factors	Analysis of High Risk Factors
x_6 Resource exploration and reserves reliability	The overall exploration level of the deposit is low, and the inferred resources account for a high proportion of total resources.
x_9 Government work efficiency	The administrative efficiency of the Zambian government is generally low, and the management of information by the government is relatively confusing.
x_{12} Policy continuity	The government encourages foreign investment, but there is a lack of continuity in the implementation of policies.
x_{16} Raw material prices	Due to a shortage of local materials, the materials required for the project must be purchased from China or South Africa, resulting in higher prices.
x_{18} Exchange rate fluctuations	The Zambian currency continuously depreciated previous years, and its ability to resist risks is relatively weak. The exchange rate may fluctuate greatly.
x_{22} Payback period	The project begins with the infrastructure period and has a long payback period.
x_{25} Labor costs	The project construction and production mainly employ local staff, and the salaries of employees are higher than those in China.
x_{26} Trade unions and labor disputes	Trade unions in the region are powerful, and there have been strikes due to labor disputes.
x_{30} Power facilities construction	Precipitation has a great impact on power supply, and insufficient precipitation will cause domestic power shortage. According to the field investigation, the local price for electricity is high.
x_{33} Mining conditions	The orebody is deeply buried with little thickness, has a small dip angle and is irregularly banded.

3. An analysis of the 10 factors with a contrary potential based on a field investigation is presented in Table 2. Clearly, these 10 factors add considerable risk to the project. The 5-element connection number that resulted from the analysis is consistent with the actual situation as verified by a field investigation. Therefore, the evaluation results can be considered credible. In the investment process, managers should focus on these factors and take appropriate improvement measures to reduce investment risk.
4. Four of the 10 high risk factors, policy continuity, raw material prices, payback period and labor costs, have risk that is trending upward. Special attention should be given to these factors. Although administrative and legal restrictions risk is currently low, it tends to increase.

4.2. Discussion

In this paper, the SPA theory was introduced into the risk evaluation of overseas mining investment, and a case study of an actual project was conducted. The research extends the application of the SPA theory, and also enriches the methods of risk evaluation in mining. The presented methodology can be applied to other similar evaluations and is scientific and extensible.

Compared with previous research, the risk evaluation method based on SPA theory uniformly treats certainty and uncertainty as a one identity-discrepancy-contrary system, which can better deal with the incomplete quantitative indexes, and fully consider the impact of uncertainty during risk assessment. The method realizes the combination of static and dynamic, qualitative and quantitative. It cannot only get the results of static risk assessment, but also dynamically recognize the trend of risk.

However, the presented method also has certain limitations. Since most of the evaluation indexes are not quantifiable, it is difficult to get the specific values. In dealing with these indexes, the expert scoring method was used to evaluate the risk factors of investment project. This makes the evaluation results partly dependent on the experts' understanding of the relevant project, although the method has reduced this effect by connection number. In the further research, we need to improve the way to obtain values of the qualitative factors, and simplify the modelling process.

Conclusions

1. Guided by the SPA theory, this study analyzes the risk factors of overseas mining investment, constructs a risk evaluation index system and establishes an identity-discrepancy-contrary risk assessment model based on the 5-element connection number. This model is applied to an actual case: a copper mine in Zambia, which is an investment project of the China Nonferrous Metals Group. By calculating the set pair potential and

the full adjacent connection number of the risk factors, the different types of risks and their trends are thoroughly evaluated.

2. The evaluation results suggest that there are 10 high risk factors in the process of project investment, and some of them still have the trend of deterioration, which should be carefully monitored. Compared to the field investigation, the practicability and effectiveness of the evaluation method are illustrated. The evaluation results can provide investors with appropriate information to enable them to conduct targeted risk management.
3. The SPA theory uniformly treats certainty and uncertainty as one identity-discrepancy-contrary system, which is a new perspective for the risk assessment of overseas mining investment. It is possible to mathematically describe and quantitatively express complex system decisions by using the 5-element connection number model to evaluate projects. This evaluation method not only determines the result of a static risk evaluation but also dynamically recognizes the trends of risk. This method combines static and dynamic factors and qualitative and quantitative information, which improves the reliability and accuracy of risk evaluation. Furthermore, this evaluation method can also be applied to other similar evaluations and has a certain scalability.

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RISK EVALUATION METHOD BASED ON SET PAIR ANALYSIS APPLIED TO OVERSEAS MINING INVESTMENT

Keywords

set pair analysis, risk evaluation, 5-element connection number, set pair potential, adjacent connection number

Abstract

Overseas mining investment generally faces considerable risk due to a variety of complex risk factors. Therefore, indexes are often based on conditions of uncertainty and cannot be fully quantified. Guided by set pair analysis (SPA) theory, this study constructs a risk evaluation index system based on an analysis of the risk factors of overseas mining investment and determines the weights of factors using entropy weighting methods. In addition, this study constructs an identity-discrepancy-contrary risk assessment model based on the 5-element connection number. Both the certainty and uncertainty of the various risks are treated uniformly in this model and it is possible to mathematically describe and quantitatively express complex system decisions to evaluate projects. Overseas mining investment risk and its changing trends are synthetically evaluated by calculating the adjacent connection number and analyzing the set pair potential. Using an actual overseas mining investment project as an example, the risk of overseas mining investment can be separated into five categories according to the risk field, and then the evaluation model is quantified and specific risk assessment results are obtained. Compared to the field investigation, the practicability and effectiveness of the evaluation method are illustrated. This new model combines static and dynamic factors and qualitative and quantitative information, which improves the reliability and accuracy of risk evaluation. Furthermore, this evaluation method can also be applied to other similar evaluations and has a certain scalability.

METODA OCENY RYZYKA OPARTA NA ANALIZIE PAR ZBIORÓW W STOSOWANIU W ZAGRANICZNYCH INWESTYCJACH WYDOBYWCZYCH

Słowa kluczowe

analiza zestawów par, ocena ryzyka, powiązanie 5 elementów, ustalenie potencjału dla pary elementów, sąsiedni element połączenia

Streszczenie

Zagraniczne inwestycje wydobywcze są narażone na znaczne ryzyko z powodu różnych czynników mających wpływ na taką działalność. Stosowane wskaźniki często zawierają elementy niepewności i nie można ich w pełni skwantyfikować. Kierując się teorią analizy par (*set par analysis*), badanie to tworzy system indeksu oceny ryzyka oparty na analizie czynników ryzyka zagranicznych inwestycji górniczych i określa wagi czynników z zastosowaniem entropii. Ponadto w artykule przedstawiono model oceny ryzyka związanego z identyfikacją rozbieżności, oparty na powiązaniu pięciu elementów. Zarówno pewność, jak i niepewność różnych ryzyk są traktowane jednolicie w tym modelu i możliwe jest matematyczne opisanie i ilościowe wyrażenie złożonych decyzji systemowych w celu oceny projektów. Ryzyko inwestycji zagranicznych i ich zmieniające się trendy są oceniane syntetycznie poprzez obliczanie sąsiedniego elementu i analizowanie ustalonego potencjału dla tej pary. Przykładem może być faktyczny zagraniczny projekt inwestycyjny dotyczący górnictwa, gdzie ryzyko inwestycji zagranicznych można podzielić na pięć rodzajów zgodnie z rachunkiem ryzyka, a następnie dokonuje się oceny modelu i uzyskuje się konkretne wyniki oceny ryzyka. Na przykładzie przedstawiono aspekty praktyczne i skuteczność tej metody oceny. Ten nowy model łączy czynniki statyczne i dynamiczne oraz informacje jakościowe i ilościowe, co poprawia wiarygodność i dokładność oceny ryzyka. Co więcej, ta metoda oceny może być również zastosowana do innych podobnych zagadnień i ma pewną skalowalność.