Environ Earth Sci (2012) 66:275–284
DOI 10.1007/s12665-011-1237-z

ORIGINAL ARTICLE

A new model of geo-environmental impact assessment of mining: a multiple-criteria assessment method integrating Fuzzy-AHP with fuzzy synthetic ranking

Shuangbing Huang · Xiao Li · Yanxin Wang

Received: 8 August 2010 / Accepted: 14 July 2011 / Published online: 17 August 2011

Abstract A new evaluation model for geo-environmental impact assessment of mining (GEIAM) is proposed. The evaluation framework in this model considers three groups of criteria, namely, geo-hazards risks, environmental risks, and resource damages. Fuzzy-analytic hierarchy process (AHP) was used to establish a multiple-criteria evaluation system and simultaneously command weighting to avoid vagueness and ambiguity in expert judgment. Membership function was employed to deal with the vagueness boundary problem of indices scoring and to help complete the ultimate fuzzy synthetic ranking. The model expresses the evaluation results with an integrated objective ranking and three criteria ranking. It was tentatively applied to assess an opencast limestone mine. The results indicated that the indices sequences were consistent with the mine background and the expert professional experience and better revealed the impact of geo-hazards risks. Specific assessment factors such as geo-hazards potential, engineering geological condition, and hydrogeological condition were prioritized for further improvement. Compared with existing GEIAM evaluation methods, the proposed assessment model focuses more on expert experience and judgment, breaks through the limitation of local estimation to variable attributes and, most importantly, satisfies the multi-purpose requirements to incorporate real considerations together for mining safety, geo-environmental protection, and natural resource conservation.

Keywords Geo-environmental impact assessment · Fuzzy-AHP · Fuzzy synthetic ranking · Mining safety · Sustainable development

Introduction

Balancing the benefits of mining activity and environmental protection is vital for the sustainable exploitation of mineral resources (Mayes et al. 2009; Jordan and Project 2009). In recent years, major efforts have been made to study environmental contamination due to mining (Monjezi et al. 2009; Jordan and Project 2009) and mining risks, such as vulnerability of buildings (Deck et al. 2009) and blast vibration impacts (Toomik 2003). One major side effect of mining is the frequent occurrence of geo-hazards, such as landslide, debris flow, and land collapse. Therefore, geological knowledge and sufficient methodological experience are necessary and important for the environmental assessment of mines (Jordan and Project 2009).

To ensure mining safety, the Chinese Ministry of Land and Resources issued a regulation enforcing geo-environmental impact assessment of mining (GEIAM), in addition to ordinary environmental impact assessment (water, air, soil, and noise contamination) required by environmental protection agencies. Such a strengthened regulation reflects the realistic understanding of national government administrators of the effects of geological factors on the environment of mining districts. To support GEIAM, evaluation models need urgently to meet the multi-purpose demands of real mining management, including simultaneously

---

S. Huang · Y. Wang (✉)
School of Environmental Studies and MOE Key Laboratory
of Biogeology and Environmental Geology,
China University of Geosciences, Wuhan 430074,
Hubei, People's Republic of China
e-mail: yx.wang@cug.edu.cn; yx.wang1108@gmail.com

X. Li
State Key Laboratory of Geo-hazards Prevention and Geological
Environment Protection, Chengdu University of Technology,
Chengdu 610059, Sichuan, People's Republic of China

promoting the environmental protection of mines and avoiding potential mining hazards. However, such models have not been well studied worldwide.

In the past few years, major work on GEIAM included identification of geological hazards or the evaluation of factors affecting human safety and health associated with mining (Li et al. 2009; Turer et al. 2008; Lai et al. 2006; Mohamed et al. 1996; Bajracharya et al. 1996; Mohamed et al. 1994). However, the factors related to GEIAM are diverse and complex; hence, there has been no widely accepted theoretical and methodological strategy to integrate the plentiful information and multiple indices. Moreover, a unique aspect of GEIAM is that assessment indices scoring mainly depends on expert personal judgment that makes the decision making vague and ambiguous. Therefore, holistic and more definitive approaches are needed to rationally construct the evaluation framework, systematically integrate information from different sources, and objectively rank assessment criteria.

Analytic hierarchy process (AHP) (Saaty 1977) is a utility theory based on decision-making techniques, which works on the assumption that complex decision-making problems can be handled by structuring them into simple and comprehensible hierarchical structures (Sadiq and Tesfamariam 2009). AHP has become one of the most commonly used methods applied in environment assessment over the past two decades (Lu et al. 2008; Qian et al. 2007; Ramanathan 2001; Varis 1989). The AHP technique involves human subjectivity in pair-wise comparison; hence, the fuzzy sets theory was incorporated and evolved into the Fuzzy-AHP method to eliminate vagueness and uncertainty. The Fuzzy-AHP method deals with the criteria scoring and judgment process by bringing the triangular fuzzy numbers to the pair-wise comparison matrix (Kwiesielewicz 1998; Vanlaarhoven and Pedrycz 1983). In the current study, the Fuzzy-AHP is expected to build a new evaluation system with multiple criteria and indices for GEIAM. The membership function, another effective fuzzy tool, is also employed to deal with the vagueness boundary problem of indices scoring to improve the ultimate fuzzy synthetic ranking. The applicability of the proposed evaluation method incorporating Fuzzy-AHP with fuzzy ranking will be demonstrated later by taking an opencast limestone mine as an example.

Key factors for GEIAM and evaluation framework development

The geo-environment of a mining district is understood here as the sum of the total of the elements (rock, soil, and groundwater) of the geosphere surrounding an orefield, which exchanges substance and energy with the air, the surface water, and the biota. The evaluation criteria and indices cannot be solely restricted to geological factors because mining and related human activities strongly interact with natural processes and geo-environment factors. Combining the previous experiences of geo-environment assessment (Li et al. 2009; Turer et al. 2008; Sarkar et al. 2007; Ghose and Majee 2002; Cheam et al. 2000; Mohamed et al. 1994) and considering the local characteristics of open-pit mining, the main factors for our GEIAM model can be categorized into three types: geo-hazards risks, environmental risks, and resource damages. The detailed description is presented below:

Geo-hazards risks

Open-pit mining can drastically change the landform and rock mass stress and induce geological disasters, such as ground subsidence, collapse, landslip, and debris flow. For geo-hazards risk evaluation, factors including topography, structural geology, hydrogeology, engineering geology, geo-hazards potential, and mining style, have to be considered and integrated.

Environmental risks

The most sensitive factors of the environmental risks of mining are generally related to the negative impacts on the water resources in or around an orefield. In most cases, the mine drainage may be discharged into the water body surface without any treatment. Furthermore, ore deposit digging or extraction can dewater aquifers and destroy the regional water balance. Furthermore, environmental risks of mining should also contain important indices reflecting atmospheric and soil contamination. However, whether to incorporate more common environment indices into the GEIAM evaluation system or not depends on the specific mine conditions and mining operation styles.

Resource damages

Another mining hazard is the resource damage exerted on both the ecological system and the geo-environment system. For open-pit mining, the main types of resource damages usually include land occupation, vegetation destruction, and geological heritage damage.

Using the analysis above as basis, the evaluation criteria can be determined. Thus, according to the AHP theory, the ultimate objective can be subdivided into three levels. The first level constitutes the integrated geo-environmental impacts of mining activity. The second level is the assessment criteria system, including geo-hazards risks, environmental risks, and resource damages. The third level consists of the concrete assessment indices that are subordinated to the criteria level and, thus, contribute to the first level. The evaluation framework of a multi-objective decision making with AHP and the evaluation method employed is depicted in Fig. 1. The evaluation procedure is formed by three main steps as follows.

Step 1. Identify the evaluation criteria that are considered as the most important factors responsible for major mining hazards.
Step 2. Construct the evaluation hierarchy structure and calculate the weights of criteria and indices by applying the Fuzzy-AHP method.
Step 3. Employ membership function to achieve the ultimate synthetic ranking.

Criteria and indices weighting by Fuzzy-AHP

Although AHP has been proven to be a utility theory in multiple-criteria assessment, it involves human subjectivity in pair-wise comparison, which introduces vagueness that necessitates the use of decision making under uncertainty (Sadiq and Tesfamariam 2009; Wang et al. 2006; Tesfamariam and Sadiq 2006). An increasing number of researchers have been concerned with vagueness problems through fuzzy sets theory (Zheng et al. 2009; Wang et al. 2009; Tesfamaraim and Saatcioglu 2008; Singh et al. 2008; Huang et al. 2008; Dahiya et al. 2007; Wang et al. 2006; Rajani et al. 2006; Garg et al. 2006; Sadiq and Rodriguez 2004; Sadiq et al. 2004; Onkal-Engin et al. 2004). A more realistic approach is to use linguistic assessments instead of numerical values to give the judgments (Chen 2000). In the current study, traditional AHP was used to construct the judgment matrix and to carry out consistency checks. Triangular fuzzy numbers is one of the most commonly used fuzzy methods, which can represent linguistic variables. Thus, it was introduced to transfer the positive reciprocal matrices to the fuzzy ones for decision making in a fuzzy environment.

Construction of comparison matrices

A comparison matrix involves the pair-wise comparison for the elements under a constructed hierarchy structure. The aim is to set the relative priority of the elements at the same level. The scores representing the relative importance were graded by an expert advice to form pair-wise comparison matrices according to a nine-point scale proposed by Saaty (1977).

$$A = \begin{array}{c|ccccc|} & C_1 & C_2 & C_3 & \cdots & C_n \\ C_1 & x_{11} & x_{12} & x_{13} & \cdots & x_{1n} \\ C_2 & x_{21} & x_{21} & x_{21} & \cdots & x_{2n} \\ C_3 & x_{31} & x_{32} & x_{33} & \cdots & x_{3n} \\ \vdots & \vdots & & & & \\ C_n & x_{n1} & x_{n2} & x_{n3} & & x_{nn} \end{array}.$$

The elements $\{x_{ij}\}$ can be interpreted as the degree preference of the ith criterion over the jth criterion.

Consistency check

The exact value weight determination and consistency validation were conducted using the method proposed in AHP. The eigenvalues and eigenvectors of the judgment matrices were calculated using Eq. (1). Parameters such as consistency index (CI) and consistency ratio (CR) were obtained from Eqs. (2) and (3) to validate the consistency of the judgments by decision makers.

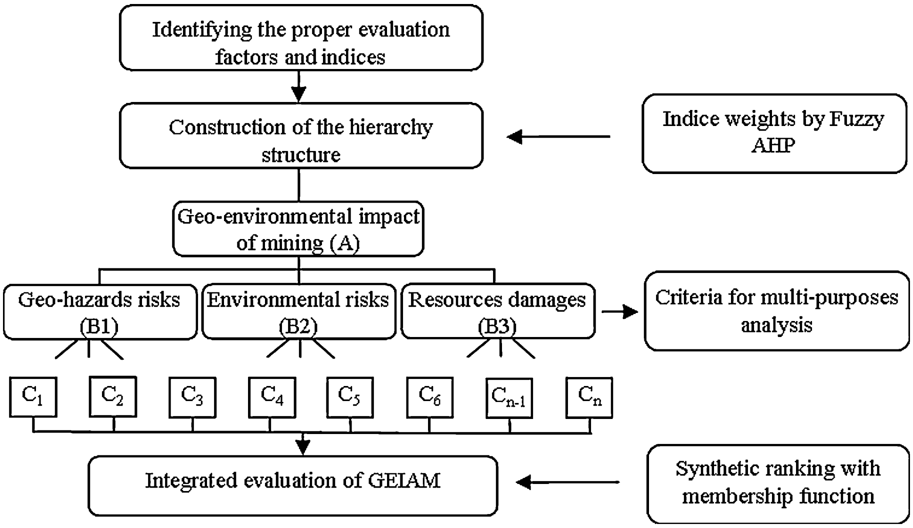

Fig. 1 Evaluation framework of GEIAM and relevant evaluation methods

$$\mathrm{AW} = \lambda_{\max}\mathrm{W} \quad (1)$$

$$\mathrm{CI} = \frac{\lambda_{\max} - \mathrm{N}}{\mathrm{N} - 1} \quad (2)$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (3)$$

where W is the eigenvector, which is also the weight vector, $\lambda_{\max}$ is the principal eigenvalue of matrix A, N is the order of the judgment matrix, and RI is a varying random index on the order of matrix (Saaty 1977). The closer the consistency ratio is to zero, the better the consistency becomes. CR should be lower than 0.1 to consider the result of the eigenvector W as an acceptable weight. Otherwise, the comparison and calculation should be redone (Table 1).

Table 1 Random index (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.96	1.12	1.24	1.32	1.41	1.45	1.49

Obtaining fuzzy weights

The fuzzy positive reciprocal matrices were produced by transforming the real elements of pair-wise comparisons matrices into linguistic variables (Buckley 1985). The correspondences of fuzzy linguistic variables with the triangular fuzzy numbers are summarized in Table 2.

According to the maximum membership degree method (Csutora and Buckley 2001), three new matrices can be formed by extracting the lower and upper bound, as well as the modal (mid) value of each triangular fuzzy number pairs from the fuzzy positive reciprocal matrix. Thus, three weight vectors were calculated using the method proposed in AHP, namely, $w_l = w_{\mathrm{il}}$, $w_m = w_{\mathrm{im}}$, and $w_u = w_{\mathrm{iu}}$.

Table 2 Linguistic variables and corresponding triangular fuzzy numbers

Linguistic variables	Positive triangular fuzzy numbers	Positive reciprocal triangular fuzzy numbers
Extremely strong	(9, 9, 9)	(1/9, 1/9, 1/9)
Intermediate	(7, 8, 9)	(1/9, 1/8, 1/7)
Very strong	(6, 7, 8)	(1/8, 1/7, 1/6)
Intermediate	(5, 6, 7)	(1/7, 1/6, 1/5)
Strong	(4, 5, 6)	(1/6, 1/5, 1/4)
Intermediate	(3, 4, 5)	(1/5, 1/4, 1/3)
Moderately strong	(2, 3, 4)	(1/4, 1/3, 1/2)
Intermediate	(1, 2, 3)	(1/3, 1/2, 1)
Equally strong	(1, 1, 1)	(1, 1, 1)

To minimize the fuzziness of the weight, two constants, K_l and K_u, are chosen:

$$K_l = \min\left\{\frac{w_{\mathrm{im}}}{w_{\mathrm{il}}} \middle| 1 \le i \le n\right\} \quad (4)$$

$$\mathrm{K}_u = \max\left\{\frac{w_{\mathrm{im}}}{w_{\mathrm{iu}}} \middle| 1 \le i \le n\right\} \quad (5)$$

The upper and lower bound weights are defined as:

$$w^*_{\mathrm{il}} = K_i w_{\mathrm{il}} \quad (6)$$

$$w^*_{\mathrm{iu}} = K_u w_{\mathrm{iu}} \quad (7)$$

The fuzzy weight matrix can be produced by combining the three weight vectors.

$$\tilde{w}_i = \left(w^*_{\mathrm{il}}, w^*_{\mathrm{im}}, w^*_{\mathrm{iu}}\right). \quad (8)$$

Defuzzification

A proximity coefficient was defined to obtain the ranking order of the decision elements according to Chen (2000). The proximity coefficient is defined as:

$$\mathrm{CC}_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (9)$$

where CC_i is the weight for the decision element i, and

$$d_i^-(w_i, 0) = \sqrt{(1/3)[(w_{\mathrm{il}} - 0)^2 + (w_{\mathrm{im}} - 0)^2 + (w_{\mathrm{iu}} - 0)^2]} \quad (10)$$

$$d_i^+(w_i, 0) = \sqrt{(1/3)[(w_{\mathrm{il}} - 1)^2 + (w_{\mathrm{im}} - 1)^2 + (w_{\mathrm{iu}} - 1)^2]} \quad (11)$$

$d_i^-(w_i, 0)$ and $d_i^+(w_i, 0)$ are the distance values between two fuzzy numbers.

Global weights (overall ranking weights)

The operations described above can be used to obtain the single index weights of one layer corresponding to the upper layer, such as the criterion level to the targeted level. The weight of the index layer (or sub-criterion) to the criterion level can be calculated using the same method. Furthermore, we can also derive the global weights from the multiplication operation of the weights of the lower layer with the upper one, which was overall ranked in the hierarchy.

Membership function and relationship matrix

Membership function is a mathematic tool for depicting the fuzzy sets, which can be simply defined as follows.

Suppose that U is a universe of discourse of a fuzzy set A. In this case, U can be called a fuzzy subset, and u is an element in U. The value of membership function (or membership degree, remarked as $\tilde{u}$) among the intervals of [0, 1] represents the degree that u belongs to U (Zadeh 2004). In the present study, a variety of geological factors for GEIAM consist of qualitative indices. In such a case, experts likewise tend to use linguistic variables such as "acceptable" or "warrantable" to evaluate indices attributes, which inevitably make experts feel uneasy to rate them in a definite way, especially when determining attributes at the edge of the rates. To solve this problem, we first set the proper numbers of rates (three rates for the current study) and the scoring guideline for all assessment attributes. We then introduced the membership function to connect the variable scores and the attribute rate by assigning each variable a membership degree. Thus, the rating process is implemented in a fuzzy environment, and the evaluation process can tolerate the presence of boundary fuzziness of attributes.

The membership function formulas will be presented in the application section of the GEIAM evaluation model. When the membership degree to every assessment variable is determined, the fuzzy evaluation matrix (relationship matrix) can be formed:

$$R^k = [r_{ij}]^k_{n\times m} \tag{12}$$

where R^k is a fuzzy relationship matrix formed by decision maker k, n is the number of the assessment indices, and m is their rating (grades).

If there are multiple experts participating in the decision-making process, the integrated fuzzy relationship matrix can be achieved by the arithmetic mean method as follows:

$$R = \left[\frac{\sum_1^k r_{ij}}{k}\right]_{n\times m} \tag{13}$$

Synthetic evaluation

We can now obtain the relative importance of each assessment criterion and the attribute measure of indices using the methods proposed in Sects. 3 and 4. In the current study, we calculate not only the importance of grades to the criterion, but also the ultimate objective level. The evaluation results can be acquired by multiplying the membership degree with the local weights of single ranking and overall weights of total ranking.

$$S = \bar{\bar{w}} \cdot R \tag{14}$$

where S is the ranking grade of the evaluation objective, $\bar{\bar{w}}$ is the weight of each assessment criterion or variable, and R is the membership degree matrix (fuzzy relationship matrix) integrated with experts grading.

Application of GEIAM evaluation model

In this section, a limestone mine surface was chosen as an example to demonstrate how the triangular fuzzy number was incorporated into AHP to help transfer expert judgment into the weight, and how the fuzzy theory was applied to achieve the ranking of assessment variables in real problems.

Background

The mine chosen for this study is the Jiguanshan limestone mine in Chongzhou County of Sichuan Province in Western China. The limestone was mined to meet the demand for the raw materials of cement to be used in reconstruction efforts after the Wenchuan earthquake on 12 May 2008. Located at 103°21′45″–103°21′45″E, 103°21′45″–103°21′45″N, the mining area is 104 km west of Chengdu, and has an area of 6.7 km^2. The limestone ore beds occur in the middle Permian System, and the mining approach was designed to be opencast working with bench. The ultimate angle of boundary slopes was set at 55°. The production capacity was designed to be 200 Wt/a. The preliminary survey data of geological and environmental conditions of the mine were collected for the current study. Three experts from the Bureau of Geology and Mineral Resources of Sichuan Province and Chengdu University of Technology, who are actively involved in geo-environmental studies, were invited to participate in the decision making during our evaluation process.

Evaluation procedure

Thirteen indices were selected according to previous experiences in geo-environment assessment practice in China and abroad. Utilizing the hierarchy frame shown in Fig. 1, a complete evaluation hierarchy structure (system) was established. The preliminary classification consists of three criteria corresponding to the selected 13 indices (subcriterions) (Table 3). Their judgment matrix was then passed through a consistency check. The four comparison matrices corresponding to the hierarchal structure were then transferred into the fuzzy matrices, in which the real elements were replaced by triangular fuzzy number pairs (Table 4). The calculated fuzzy weights for single ranking are summarized in Table 5.

According to the expert experience and knowledge about the mine area, the indices scoring and rating guideline for the degree of geological environmental

Table 3 Evaluation hierarchy structure for Jiguanshan limestone mine in Chongzhou, Sichuan

Objective	Criteria	Sub-criteria (indices)
Geo-environmental impacts of mining [A1]	Geo-hazards risks [B1]	Topography [C1]
		Structural geology [C2]
		Hydrogeology [C3]
		Engineering geology [C4]
		Geo-hazards potential [C5]
		Mining approach [C6]
	Environmental risks [B2]	The quality of groundwater [C7]
		The quantity of groundwater [C8]
		Quality of surface water [C9]
		Quantity of surface water [C10]
	Resource damages [B3]	Land occupation [C11]
		Vegetation destruction [C12]
		Damage of geological heritage sites [C13]

Table 4 Triangular fuzzy number matrices

A	B1	B2	B3	–	–	–
[B1]	(1, 1, 1)	(2, 3, 4)	(4, 5, 6)	–	–	–
[B2]	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 2, 3)	–	–	–
[B3]	(1/6, 1/5, 1/4)	(1/3, 1/2, 1)	(1, 1, 1)	–	–	–
B1	[C1]	[C2]	[C3]	[C4]	[C5]	[C6]
[C1]	(1, 1, 1)	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	(1/5, 1/4, 1/3)	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)
[C2]	(1, 2, 3)	(1, 1, 1)	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	(1/5, 1/4, 1/3)	(1/3, 1/2, 1)
[C3]	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)
[C4]	(3, 4, 5)	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(1/3, 1/2, 1)	(1, 2, 3)
[C5]	(4, 5, 6)	(3, 4, 5)	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(2, 3, 4)
[C6]	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(1/3, 1/2, 1)	(1/4, 1/3, 1/2)	(1, 1, 1)
B2	[C7]	[C8]	[C9]	[C10]	–	–
[C7]	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1/5, 1/4, 1/3)	–	–
[C8]	(2, 3, 4)	(1, 1, 1)	(1, 2, 3)	(1/3, 1/2, 1)	–	–
[C9]	(1, 2, 3)	(1/3, 1/2, 1)	(1, 1, 1)	(1/4, 1/3, 1/2)	–	–
[C10]	(3, 4, 5)	(1, 2, 3)	(2, 3, 4)	(1, 1, 1)	–	–
B3	[C11]	[C12]	[C13]	–	–	–
[C11]	(1, 1, 1)	(2, 3, 4)	(1/5, 1/4, 1/3)	–	–	–
[C12]	(1/4, 1/3, 1/2)	(1, 1, 1)	(1/4, 1/3, 1/2)	–	–	–
[C13]	(3, 4, 5)	(2, 3, 4)	(1, 1, 1)	–	–	–

impacts of mining have been identified and are listed in Table 6. The problem of classifying GEIAM variable attributes was addressed using a combination of designed fuzzy membership functions. An input membership function defined the fuzzy sets by mapping crisp inputs from the assessment variables scoring domain (from 0 to 10) to degrees of membership (from 0 to 1). Both triangular and trapezoidal fuzzy membership functions were applied to delineate the classification of variable attributes into "warrantable", "acceptable", and "unwarrantable," respectively. The relevant three membership function formulas are given in Eqs. (15) to (17). The graphical presentation of the membership function is shown in Fig. 2.

$$\text{Warrantable}: r_{i1} = \begin{cases} 1 & c_i \leq 2 \\ \frac{5-c_i}{3} & 2 \leq c_i \leq 5 \\ 0 & c_i > 5 \end{cases} \tag{15}$$

$$\text{Acceptable}: r_{i2} = \begin{cases} \frac{c_i-2}{3} & 2 \leq c_i \leq 5 \\ \frac{8-c_i}{3} & 5 \leq c_i \leq 8 \\ 0 & c_i > 8, c_i < 2 \end{cases} \tag{16}$$

$$\text{Unwarrantable}: r_{i3} = \begin{cases} \frac{c_i-5}{3} & 5 \leq c_i \leq 8 \\ 1 & c_i \geq 8 \\ 0 & c_i < 5 \end{cases} \tag{17}$$

Using the arithmetic mean method shown in Eq. (13), the integrated scores of the experts for each variable were

Table 5 Fuzzy weights for single criterion

Fist level	Second level	Fuzzy weights	Third level	Fuzzy weights
[A]	[B1]	(0.630, 0.648, 0.648)	[C1]	(0.050, 0.051, 0.055)
			[C2]	(0.070, 0.080, 0.094)
			[C3]	(0.126, 0.135, 0.146)
			[C4]	(0.187, 0.231, 0.254)
			[C5]	(0.318, 0.365, 0.366)
			[C6]	(0.126, 0.135, 0.146)
	[B2]	(0.198, 0.229, 0.258)	[C7]	(0.095, 0.095, 0.105)
			[C8]	(0.237, 0.277, 0.307)
			[C9]	(0.140, 0.160, 0.183)
			[C10]	(0.408, 0.467, 0.467)
	[B3]	(0.122, 0.122, 0.143)	[C11]	(0.215, 0.247, 0.269)
			[C12]	(0.118, 0.130, 0.150)
			[C13]	(0.548, 0.622, 0.643)

Table 6 Guideline to indices scoring and rating to the degree of GEIAM

Indices	Rates to attributes of assessment variables (indices)		
Grades	1	2	3
	Warrantable	Acceptable	Unwarrantable
	0–3.5	3.5–6.5	6.5–10
[C1]	Singular geomorphology type; the depth of erosion is below 300 m	Few geomorphology types; the depth of erosion varies between 300 and 500 m	Various geomorphology types; the depth of erosion is more than 500 m
[C2]	Geological structure is simple, no history of neotectonic movement, host rocks (beds) are stable	Faults occur; there is no neotectonic activities; host rocks (beds) are stable	Fault well developed, neotectonic activities are frequent; host rocks (beds) are unstable
[C3]	The ore bodies are higher than the local base level of erosion; no flooding risks; bad recharge and good discharge conditions; simple hydrogeological boundary	The ore bodies are below the local base level of erosion; low flooding risk. Normal recharge and discharge conditions; relatively complex hydrogeological boundaries	The ore bodies are below the local base level of erosion; high flooding risk; good recharge and bad discharge condition; complex hydrogeological boundaries
[C4]	Thick bedded hard rock, no cracks; high mechanical strength	Thick bedded hard rock, cracks exist; relatively high mechanical strength	Weak rock; cracks occur frequently
[C5]	No geo-hazard; the strike of slope is opposite to the rock bedding	Single type of geo-hazard; the strike of slope is oblique to the rock bedding	Large-scale composite-type geo-hazards occurred; the strike of slope is in accordance with rock bedding
[C6]	The mine production is less than 100 Wt; the management of mining operation is scientific and rational	The mine production is between 50 and 100 Wt; the management of mining operation is rational basically.	The mine production is more than 100 Wt; the management of mining is not scientific and rational
[C7]	Stable hydrochemistry	Changing hydrochemistry	Groundwater quality changed obviously or poisonous indicators were detected
[C8]	Stable groundwater regime	Fluctuating groundwater regime	Balance of groundwater regime destroyed
[C9]	Surface water quality is stable and unchanged	Chemical and hygiene parameters of surface water quality changed	Intensive changes of surface water quality or poisonous indicators were detected
[C10]	No surface water body nearby or no impact on it	The impact on surface water flow was slight	The flow of surface water body was cut off or dried up
[C11]	The area of occupied land is small; discharge of solid wastes has no impacts on environment	The area of occupied land is intermediate; discharge of solid wastes exerts side effects on environment	Large areas of land are occupied; discharge of solid wastes produces environmental impacts
[C12]	No vegetation cover in mining area, or industrial activity did not destroy the vegetation	A small amount of vegetation was destroyed	Great destruction of vegetation
[C13]	There is no geological heritage sites or any bad effect on them	Limited negative effect on geological heritage sites	Geological heritage sites were drastically damaged

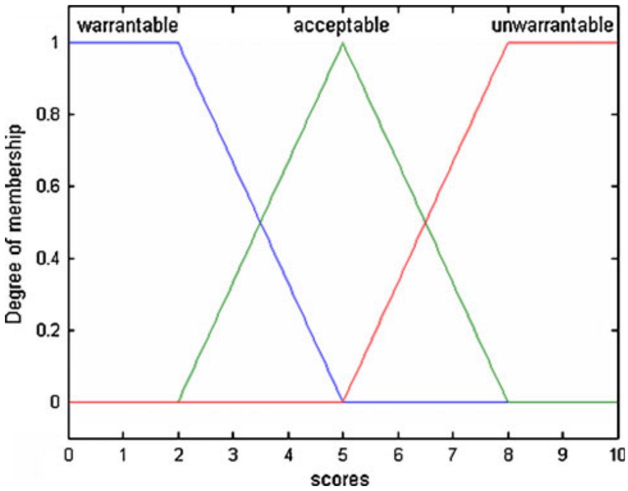

Fig. 2 Membership function

calculated. The fuzzy relationship matrix was then obtained by inputting the scores to the constructed membership function (Table 7). After finishing the last weighting procedure, which is defuzzification, we could manipulate the synthetic evaluation by integrating the weight vector and the fuzzy relationship matrix. The ranking results in a single criterion and the ultimate objective level, listed in Table 7.

Results and discussion

Two ranking calculations were made during the evaluation process for both the single criterion and the overall level.

The first calculation was done to obtain the weights of criteria and indices, whereas the second rank was for evaluation purposes. "Weights" represents the relative status of the assessment criteria to the upper criterion or the objective level for the expert, whereas the ultimate ranking reflects the priority subordinated to the attribute rates for evaluation purposes. With respect to the former, the experts do judgment focusing on the intrinsic geological characteristic and regional geo-environmental background. However, the ultimate sequencing is intended to represent the real performance on both the geological environment conditions and the mining method design.

Sensitivity analysis to sequencing results

The weight vector for the criterion level (0.662, 0.052, and 0.013) was obtained (Table 7). The vector represents the relative importance sequence of the assessment criteria to GEIAM: geo-hazard risks > environmental risks > resource damages. The assessment for indices under criterion level B1, or geo-hazard risks, is C5 > C4 > C3 = C6 > C2 > C1, whereas that under level B2, or environmental risks, is C10 > C8 > C9 > C7. The results of the weights sequences are consistent with the real geological environmental background of Jiguanshan limestone mine. The vulnerable geological environmental conditions are characterized by the intermittent occurrence of geological disasters such as landslide and debris flow, resulting from the aftershock of the MS8.0 Wenchuan earthquake. In addition, the orefield is located upstream of a small village

Table 7 Weights, fuzzy relationship matrix and the evaluation results for both single-level and total ranking

Variables	Weights for criteria	Weights for sub-criteria	Total ranking weights	Fuzzy relationship matrix R			Ranking results
[C1]		0.002	0.0008	0.58	0.417	0	–
[C2]		0.005	0.0019	0.5	0.500	0	–
[C3]	0.662	0.015	0.0057	0.83	0.167	0	–
[C4]		0.05	0.0177	0	0.917	0.083	–
[C5]		0.152	0.0502	0	0.667	0.333	–
[C6]		0.015	0.0057	0	0.583	0.417	–
[C7]		0.007	0.0003	0.92	0.083	0	–
[C8]	0.052	0.082	0.0029	0.67	0.333	0	–
[C9]		0.022	0.001	1	0	0	–
[C10]		0.289	0.0071	0.67	0.333	0	–
[C11]		0.061	0.0007	0	1	0	–
[C12]	0.013	0.014	0.0002	0	0.833	0.167	–
[C13]		0.602	0.0045	1	0	0	–
B1	–	–	–	0.0161	0.162	0.061	2
B2	–	–	–	0.277	0.123	0	1
B3	–	–	–	0.602	0.073	0.002	1
A	–	–	–	0.0186	0.060	0.020	2

and a river, and mining activities may affect the water quality of the river. Therefore, the local people are under threat of geo-hazards and surface water quality degradation. Experts graded the indices weights in level B1 and B2 based on the understanding of these characteristics. With regard to the indices scoring of resource damage level, experts judge according to common professional experience. Normally, the geological heritage is deemed to be priceless, because it is irreplaceable and usually has a long geological history period of formation and land use area of opencast mining is very large. Thus, the result ranked for B3 is C13 > C11 > C12.

Assessment results and implications

On the principle of membership degree, the overall evaluation (ranking) turned out to be 2 (Table 7), which shows that the result of GEIAM is acceptable. The evaluation implies that the applying mine can be accessed by authorities, while further measures should be taken to improve the conditions. Furthermore, the rankings for the single criterion B1, B2, and B3, are 2, 1, and 1, respectively, indicating that the estimated performance of geo-hazards risks, environmental risks, and resource damages is acceptable, warrantable, and warrantable, respectively. The rankings suggest that environmental impacts and resource damages will not pose a threat to geological environment with the current geo-environmental conditions and designed mining method, but the geo-hazards risk may do so. Specifically, the geo-hazards potential, engineering geological condition, hydrogeological condition, and mining style should be matters of concern according to the index ranking included in the assessment results (Table 7).

Conclusions

The evaluation model of GEIAM serves as a tool for the management of and decision making on mining activity, and is expected to involve the complex aspects of the physical conditions of mines. The new evaluation model proposed in this paper employs a multiple-criteria assessment to meet multi-purpose demands. The model categorized the geological environmental impacts into three types, namely, geo-hazards risks, environmental risks, and resources damages, to evaluate their performances. Fuzzy-analytic hierarchy process (AHP) was used to establish a multiple-criteria evaluation system and simultaneously command weighting, which makes the judgment process cater more to expert minds by introducing a triangular fuzzy number. Thus, it eases the judgment/comparison process. Membership function was employed to complete the ultimate fuzzy synthetic ranking. The merits include providing a solution to the vagueness boundary problem of indices scoring, and enabling the ranking in a holistic way rather than limiting it to the local aspect.

A tentative assessment of an opencast limestone mine has indicated that the indices sequences are consistent with the background of mines and the professional experience of the expert. The overall evaluation turned out to be an "acceptable" result for GEIAM, which implies that the applying mine can still be accessible after further improvements are made. The ranking result for the single criterion suggests that the geo-hazards risk associated with mining may pose a threat to the geological environment. Mining applicants could focus on improved efforts in the prevention of geo-hazards risk. The evaluation result highlights the underperformed aspects and prioritizes the specific factors for further improvement.

The proposed methodology for GEIAM represents a new evaluation model for the mine environment, as well as an integrated multiple-criteria assessment method combining Fuzzy-AHP with fuzzy synthetic ranking. The methodology provides the environmental regulators of the mine and concerned groups with a definitive objective assessment methodology for mine management. Compared with existing GEIAM evaluation methods, the proposed method focuses more on the experience and judgment of experts, overcomes the limitation of local estimation to the attributes, and most importantly satisfies the multi-purpose requirements to incorporate real considerations together for mining safety, geo-environmental protection, and natural resource conservation.

Acknowledgments The research work was financially supported by the National Natural Science Foundation of China (40830748). The language of the manuscript was improved with the help of Martin J. Booth and Angela P. Rangel. The manuscript benefited a lot from the constructive comments of Dr. James W. LaMoreaux and three anonymous reviewers.

References

Bajracharya K, Barry DA, Culligan PJ (1996) Geo-environmental assessment of a micaceous soil for its potential use as an engineered clay barrier—discussion. Geotech Test J 19:452–453

Buckley JJ (1985) Fuzzy hierarchical analysis. Fuzzy Set Syst 17:233–247

Cheam V, Garbai G, Lechner J, Rajkumar J (2000) Local impacts of coal mines and power plants across Canada. I. Thallium in waters and sediments. Water Qual Res J Can 35:581–607

Chen CT (2000) Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy Set Syst 114:1–9

Csutora R, Buckley JJ (2001) Fuzzy hierarchical analysis: the lambda-max method. Fuzzy Set Syst 120:181–195

Dahiya S, Singh B, Gaur S, Garg VK, Kushwaha HS (2007) Analysis of groundwater quality using fuzzy synthetic evaluation. J Hazard Mater 147:938–946

Deck O, Verdel T, Salmon R (2009) Vulnerability assessment of mining subsidence hazards. Risk Anal 29:1381–1394

Garg A, Achari G, Joshi RC (2006) A model to estimate the methane generation rate constant in sanitary landfills using fuzzy synthetic evaluation. Waste Manage Res 24:363–375

Ghose MK, Majee SR (2002) Assessment of the status of work zone air environment due to opencast coal mining. Environ Monit Assess 77:51–60

Huang M, Ip WH, Yang HM, Wang XW, Lau HCW (2008) A fuzzy synthetic evaluation embedded tabu search for risk programming of virtual enterprises. Int J Prod Econ 116:104–114

Jordan G, Project JP (2009) Sustainable mineral resources management: from regional mineral resources exploration to spatial contamination risk assessment of mining. Environ Geol 58:153–169

Kwiesielewicz M (1998) A note on the fuzzy extension of Saaty's priority theory. Fuzzy Set Syst 95:161–172. doi:10.1016/s0165-0114(96)00329-6

Lai XP, Cai MF, Ren FH, Xie MW, Esaki T (2006) Assessment of rock mass characteristics and the excavation disturbed zone in the Lingxin Coal Mine beneath the Xitian River, China. Int J Rock Mech Min 43:572–581

Li WP, Wen DG, Zhou AG, Sun XM, Meng H, Shi JS, Chen ZY, Zhang LQ, Feng XM, Liu CL, Zhou JW (2009) Assessment of geological security and integrated assessment geo-environmental suitability in worst-hit areas in Wenchuan quake. Acta Geol Sin Engl 83:816–825

Lu H, Yi GD, Tan JR, Liu ZY (2008) Collision avoidance decision-making model of multi-agents in virtual driving environment with analytic hierarchy process. Chin J Mech Eng 21:47–52

Mayes WM, Johnston D, Potter HAB, Jarvis AP (2009) A national strategy for identification, prioritisation and management of pollution from abandoned non-coal mine sites in England and Wales. I. Methodology development and initial results. Sci Total Environ 407:5435–5447

Mohamed AMO, Yong RN, Tan BK, Farkas A, Curtis LW (1994) Geo-environmental assessment of a micaceous soil for its potential use as an engineered clay barrier. Geotech Test J 17:291–304

Mohamed AMO, Yong RN, Tan BK, Farkas A, Curtis LW (1996) Geo-environmental assessment of a micaceous soil for its potential use as an engineered clay barrier—closure. Geotech Test J 19:453–456

Monjezi M, Shahriar K, Dehghani H, Namin FS (2009) Environmental impact assessment of open pit mining in Iran. Environ Geol 58:205–216

Onkal-Engin G, Demir I, Hiz H (2004) Assessment of urban air quality in Istanbul using fuzzy synthetic evaluation. Atmos Environ 38:3809–3815

Qian Y, Huang ZX, Yan ZG (2007) Integrated assessment of environmental and economic performance of chemical products using analytic hierarchy process approach. Chin J Chem Eng 15:81–87

Rajani B, Kleiner Y, Sadiq R (2006) Translation of pipe inspection results into condition ratings using the fuzzy synthetic evaluation technique. J Water Supply Res T 55:11–24

Ramanathan R (2001) A note on the use of the analytic hierarchy process for environmental impact assessment. J Environ Manage 63:27–35

Saaty TL (1977) A scaling method for priorities in hierarchical structures. J Math Psychol 15:234–281. doi:10.1016/0022-2496(77)90033-5

Sadiq R, Rodriguez MJ (2004) Fuzzy synthetic evaluation of disinfection by-products—a risk-based indexing system. J Environ Manage 73:1–13

Sadiq R, Tesfamariam S (2009) Environmental decision-making under uncertainty using intuitionistic fuzzy analytic hierarchy process (IF-AHP). Stoch Env Res Risk A 23:75–91

Sadiq R, Husain T, Veitch B, Bose N (2004) Risk-based decision-making for drilling waste discharges using a fuzzy synthetic evaluation technique. Ocean Eng 31:1929–1953

Sarkar BC, Mahanta BN, Saikia K, Paul PR, Singh G (2007) Geo-environmental quality assessment in Jharia Coalfield, India, using multivariate statistics and geographic information system. Environ Geol 51:1177–1196

Singh B, Dahiya S, Jain S, Garg VK, Kushwaha HS (2008) Use of fuzzy synthetic evaluation for assessment of groundwater quality for drinking usage: a case study of Southern Haryana, India. Environ Geol 54:249–255

Tesfamaraim S, Saatcioglu M (2008) Seismic risk assessment of RC buildings using fuzzy synthetic evaluation. J Earthq Eng 12:1157–1184

Tesfamariam S, Sadiq R (2006) Risk-based environmental decision-making using fuzzy analytic hierarchy process (F-AHP). Stoch Env Res Risk A 21:35–50

Toomik A (2003) Retrospective environmental assessment of blast vibration impact in underground mining. Oil Shale 20:127–133

Turer D, Nefeslioglu HA, Zorlu K, Gokceoglu C (2008) Assessment of geo-environmental problems of the Zonguldak province (NW Turkey). Environ Geol 55:1001–1014

Vanlaarhoven PJM, Pedrycz W (1983) A fuzzy extension of Saaty's priority theory. Fuzzy Set Syst 11:229–241

Varis O (1989) The analysis of preferences in complex environmental judgments—a focus on the analytic hierarchy process. J Environ Manage 28:283–294

Wang XY, Hou CZ, Yuan JM, Liu ZW (2006) An AHP-fuzzy synthetic evaluation model based on evidence theory. Lect Notes Artif Int 4114:108–113

Wang JH, Lu XG, Jiang M, Li XY, Tian JH (2009) Fuzzy synthetic evaluation of wetland soil quality degradation: a case study on the Sanjiang Plain, Northeast China. Pedosphere 19:756–764

Zadeh LA (2004) Membership functions and probability measures of fuzzy sets—comment. J Am Stat Assoc 99:880–881. doi:10.1198/016214504000001222

Zheng W, Chen WM, Zhu Y, Zhan P (2009) A synthetic evaluation and fuzzy scheduling model for autonomous test priority. J Test Eval 37:637–642