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Evaluation on Coal Miner's Emergency Response Capacity Based on the Catastrophe Theory and Triangular Fuzzy Number

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Abstract

The production environment of coal mine is complex and tough, so once dangerous situation appears it requires coal miners take accurate and effective emergency measures. Actually, the occurrence and further expansion of a large number of mining accidents are associated with coal miners' mishandling of emergency. Therefore, evaluating coal miners' emergency response capacity is the significant way to improve the coal miners' emergency response capacity level and pre-control coal mine accidents. Considering the drawbacks of traditional evaluation methods, this paper introduced the principle of catastrophe theory in evaluation, and proposed the evaluation model of coal miner's emergency response capacity by introducing the triangular fuzzy number theory in order to reduce the uncertainties of underlying index grades made by experts. In this method, the importance and quantitative process of each assessing indices were determined by the intrinsic mechanism of the normalized formula in catastrophe model, thus the problems of estimating the assessing index weights were avoided and the effect of subjective factors was mitigated. Finally, the verification of evaluation was implemented on specific example, and the results show that this evaluation method is reasonable, feasible, exact, and stable.

Keywords: coal miners, catastrophe theory, emergency response capacity, triangular fuzzy number, evaluation

1. Introduction

Coal mine is a special industry and the production environment is complex and tough. Miners always work underground for a long time and face all kinds of emergencies at any time. Once near miss is coming around, they have to take effective emergency response measures timely and accurately, so this requires them keep a high degree of vigilance at all times. Actually, the occurrence and further expansion of a large number of mining accidents are associated with coal miners' mishandling of emergency. For example: A gas explosion occurred in a coal mine in Jilin Province, some of the miners could not use the right methods to save themselves, at the same time as emergency rescue was not timely, not clear division of labor, resulting in 18 people were killed. So further study on miners' emergency reaction when facing coal mining emergency situation is necessary， and the scientific assessment of the individual's ability to cope with emergencies are of great significance for preventing coal emergencies and reducing the loss of accidents. But current researches in emergency field focus on mechanism, system, emergency supplies scheduling and macro emergency management, the researches on individuals specifically, especially the miners' emergency response and emergency capability assessment are rare. Some scholars carried out relevant research on health care workers and public emergency response capabilities. For example, Hammad et al. (2011) used the method of questionnaire to test emergency ability of the nurse of every large city emergency center in South America (Hammad & Arbon, 2011). Lawson et al. (2012) recorded the researchers for emergency response measures by sudden emergency scenario description of events and compared with practical response measures to find out the correlation between the actual responding ability and emergency prediction ability to the body, then proposes a new forecast method on emergency response capacity (Lawson, Sharples, Clarke, & Cobb, 2012). In addition, some other scholars also have done related research (Yi, George, Paul, & Lin, 2010; Spranger, Villegas, Kazda, Harris, Mathew, & Migala, 2007; Woodcock & Au, 2013; Ford & Schmidt, 2000). Some Chinese scholars researched the city residents public or emergency response ability evaluation (Wang & Sun, 2011; Yang & Wang, 2009; Yang, 2011; Jiang, 2011; Qian, Tang, & Zhou, 2003; Qian, Tang, & Zhou, 2006). Deng et al. (2012) researched the measure problem of commanders' emergency responding ability by investigating physiological indexes, such as galvanic skin, heart rate and beta (Deng, Meng, & Liu, 2012). Zhang et al. (2012) studied miners emergency capability assessment based on the individual's physiological parameters, and selected of seven physiological index to reflects the situation of miners' emergency disposal ability a certain extent, proposed the miners emergency capability evaluation index and calculation method (Zhang, Fu, Chen, Gao, & Zhao, 2012). How is the level of Miner's emergency response capacity? Whether the miners have the proper emergency skills and qualities? They are still pending issues. In view of this, the paper uses the catastrophe theory to explore the way to solve the problem of the scientific evaluation on miners' emergency ability.

2. The Evaluation Index System of Coal Miner's Emergency Response Capacity

Based on previous studies of individual emergency response ability, in line with the principle of comprehensive, dynamic, pertinence and operability, the paper built emergency capability evaluation index system of the miners from three dimensions: preparation beforehand u, interim response actions v and afterwards restored w. Preparation beforehand u is composed of emergency awareness u_1, emergency knowledge and skill v_1 and The understand situation of disasters w_1. Interim response actions v is composed of risk identification ability u_2, quick reaction ability v_2, self-help ability w_2 and mutual aid ability t_2. Restoration afterwards w is composed of responsibility consciousness of disaster prevention and reduction u_3, disaster reduction ability v_3 and Psychological counseling ability w_3. It is shown in Table 1.

Table 1. The evaluation index system of coal miner's emergency response capacity

Overall index	First-class	Second-class
Coal Miner's Emergency Response Capacity x	Preparation beforehand u	Emergency awareness u_1
		Emergency knowledge and skill v_1
		The understand situation of disasters w_1
	Interim response actions v	Risk identification ability u_2
		Quick reaction ability v_2
		Self-help ability w_2
		Mutual aid ability t_2
	Restoration afterwards w	Responsibility consciousness of disaster prevention and reduction u_3
		Disaster reduction ability v_3
		Psychological counseling ability w_3

3. Evaluation Model of Coal Miner's Emergency Response Capacity Based on Catastrophe Theory

3.1 The Selection of Evaluation Methods

Application of traditional evaluation methods, such as analytic hierarchy process (AHP), fuzzy comprehensive evaluation, factor analysis, gray system and Group decision making, all need to get the weight of each index which is scored by experts So the result is affected by the subjective feeling and experience of evaluation subject and has strong uncertainty. The determination of weight problem is difficult to be scientific and effective. Based on this, the article selects Catastrophe Progression Method (CPM), which is a kind of comprehensive evaluation method developed based on Catastrophe theory (Fan & Liu, 2010). In this method the importance and quantitative process were determined by the intrinsic mechanism of the normalized formula in catastrophe model. As long as clear the primary and secondary relations during assessing indexes it can be applied (Wang, Liu, Zhang, & Chen, 2011). Catastrophe theory can overcome the disadvantage of determining index weight of the traditional evaluation method to the evaluation analysis of multiple attribute decision making problems. Combining qualitative analysis and quantitative calculation to reduce the subjectivity and improve the scientific nature, rationality of the evaluation results and the calculating process is simple and the calculation results are accurate (Fan & Liu, 2010).

3.2 The Principle of Catastrophe Theory Evaluation Method

Catastrophe Theory by analyzing the system potential function $f(x)$ close to the tipping point for any "discontinuity", to realize system definition and control of mutations (Lin & Zhang, 2009; Shi, Zhang, & Liu et al., 2006). When $f'(x) = 0$, it will receive the balance of the system surface equation， and when $f''(x)=0$, it can be obtained singularity sets of the balance surface，and the bifurcation equation can be derived that reflect the relationships between state variables and control variables according to $f'(x) = 0$ and $f''(x) = 0$ (Yuan, Li, & Tian, 2011). On the basis of the Catastrophe Theory, the points on bifurcation set are critical points that might lead to system mutation. The evaluation method based on catastrophe theory gets the normalized formula by decomposed bifurcation equation; uses normalized formula for quantitative and recursive computation and obtains the total mutations function values of characterization the system status features. The normalized formula of common catastrophe model and major and minor relationship between control variables are shown in Table 2.

Table 2. The normalized formula and control variable's relation of common catastrophe model

Mutation types	state variable	controlled variable	normalized formula	control variable's relation
sharp point	1(*x*)	2(*u*,*v*)	$x_u = u^{1/2}$，$x_v = v^{1/3}$	*u*→*v*
swallow tail	1(*x*)	3(*u*,*v*,*w*)	$x_u = u^{1/2}$，$x_v = v^{1/3}$，$x_w = w^{1/4}$	*u*→*v*→*w*
butterfly	1(*x*)	4(*u*,*v*,*w*,*t*)	$x_u = u^{1/2}$，$x_v = v^{1/3}$，$x_w = u^{1/4}$，$x_t = t^{1/5}$	*u*→*v*→*w*→*t*
wigwam	1(*x*)	5(*u*,*v*,*w*,*t*,*e*)	$x_u = u^{1/2}$，$x_v = v^{1/3}$，$x_w = u^{1/4}$，$x_t = t^{1/5}$，$x_e = e^{1/6}$	*u*→*v*→*w*→*t*→*e*

According to the different nature of practical problems, the evaluation method based on catastrophe theory can adopt the following three different standards (Wang, Liu, Zhang, & Chen, 2011; Lin & Zhang, 2009; Shi, Zhang, & Liu et al., 2006; Yuan, Li, & Tian, 2011):

(1) Non-complementary principle. It's selected state variable x value according to the " minimax " principle，if the roles of various control variables cannot substitute for each other, and make up for its shortcomings with each other.

(2) Complementarity principle. That means if many control variables can compensate each other, and select the state variable *x* by the average value of control variables.

(3) Complementarity principle of exceeding the threshold value. That means many of the control variables must reach a certain threshold before complementary, selecting the state variable *x* by taking the average values of control variables after threshold.

3.3 Data Preprocessing Based on Triangular Fuzzy Number

In order to better deal with the uncertainty of experts scored on the underlying index, the fuzziness of the evaluation results and to make it closer to reality, the article introduces triangular fuzzy numbers to preprocess the data, with the aid of total mutations function value of different evaluators (λ and α take different values in formula (2)) on the evaluation results for robustness analysis.

Fuzzy number is a fuzzy set which made by the interval value of accurate real number and real number, using a triple to represent the membership functions of fuzzy number, the corresponding relationship between them is as follows:

$$\begin{cases} (1,1,2) & x = 1 \\ (x-1, x, x+1) & x = 2,3,4,5,6,7,8 \qquad x \text{ as a fuzzy number} \\ (8,9,9) & x = 9 \end{cases} \tag{1}$$

Suppose on one index, fuzzy number to get the evaluation membership function is $T=(t_1,t_2,t_3)$ by a number of experts. Make λ as confidence level of evaluators, $\lambda \in [0,1]$, for optimism evaluators λ=0; for robust evaluator λ=0.5; for pessimistic evaluator λ=1. α represent cut set. Make $D_\alpha^\lambda(i)$ as the confidence degree of evaluation object of the number *i*:

$$D_\alpha^\lambda(i) = \lambda((t_2 - t_1)\cdot\alpha + t_1) + (1-\lambda)(t_3 - (t_3 - t_2)\cdot\alpha) \tag{2}$$

For each index of complex system, the degree of confidence value can be seen as initial membership function value of index (Shi, Zhang, & Liu et al., 2006; Yuan, Li, & Tian, 2011; Liu, & Shi, 2004).

3.4 Steps of Evaluation Method of Miners Emergency Response Capability Based on Catastrophe Theory

(1) Based on the above established evaluation index system of miners emergency response capability, analyze influence degree of each index on the upper level index and clear relationship between the primary and secondary indexes.

(2) Set evaluation criteria and rating scale. In order to preprocess data conveniently with triangular fuzzy number, evaluation criteria select "1~9" numerical evaluation of the additive scaling language. Divide the level of miners' emergency response capability into five levels, as is shown in Table 3.

Table 3. Classification of coal miner's emergency response capacity evaluation

Level	Level Ⅰ	Level Ⅱ	Level Ⅲ	Level Ⅳ	Level Ⅴ
Scale	（0,0.6）	[0.6,0.7）	[0.7,0.8）	[0.8,0.9）	[0.9,1.0）

(3) Collect the experts' evaluation data on the underlying indexes of the index system, and calculate the confidence value degree of different types of evaluators (λ, α take different values in formula (2)) for each index by using the method of triangular fuzzy number to preprocess the raw data of underlying indexes (control variables), that is the initial membership function value of indexes.

(4) The function value of underlying indexes was calculated by using recursive normalized formula of catastrophe theory to get the numerical mutation level of underlying indexes. According to the three evaluation criteria based on catastrophe theory to calculate the mutation level of various indexes until get the system overall mutation membership function value.

(5) According to the total mutations membership function value of different experts (λ, α take different values in formula (2)) to do robustness analysis of the evaluation results and then obtain the final evaluation results.

4. Application Instance

(1) Invite seven professors (seniority > 15 years) engaged in coal mine safety management research, formed a experts group to evaluate the two coal miners' emergency response capabilities by taking conversation with them and simulation of emergency (one works in coal for 3 years and the other one is a new miners) according to the above indexes system, as shown in Table 4.

Table 4. The original evaluation data of coal miner's emergency response capacity

index / object	u			v				w		
	u_1	v_1	w_1	u_2	v_2	w_2	t_2	u_3	v_3	w_3
Miner 1	7	5	4	3	4	5	5	3	4	2
Miner 2	8	7	5	7	5	8	5	5	6	5

(2) According to formula (1), (2) of triangular fuzzy number to preprocess the value of experts grading underlying indexes (controlled variable) for Miner 1 and calculate the confidence level of different experts (λ, a take different value). Different decision-makers' confidence value on each index is shown in Table 5.

Table 5. Different decision-makers' confidence value on each index

λ	a	$D_\alpha^\lambda(u_1)$	$D_\alpha^\lambda(v_1)$	$D_\alpha^\lambda(w_1)$	$D_\alpha^\lambda(u_2)$	$D_\alpha^\lambda(v_2)$	$D_\alpha^\lambda(w_2)$	$D_\alpha^\lambda(t_2)$	$D_\alpha^\lambda(u_3)$	$D_\alpha^\lambda(v_3)$	$D_\alpha^\lambda(w_3)$
	0.1	6.100	4.100	3.100	2.100	3.100	4.100	4.100	2.100	3.100	1.100
	0.3	6.300	4.300	3.300	2.300	3.300	4.300	4.300	2.300	3.300	1.300
1	0.5	6.500	4.500	3.500	2.500	3.500	4.500	4.500	2.500	3.500	1.500
	0.7	6.700	4.700	3.700	2.700	3.700	4.700	4.700	2.700	3.700	1.700
	0.9	6.900	4.900	3.900	2.900	3.900	4.900	4.900	2.900	3.900	1.900
0.5	0~1	7.000	5.000	4.000	3.000	4.000	5.000	5.000	3.000	4.000	2.000
	0.1	7.900	5.900	4.900	3.900	4.900	5.900	5.900	3.900	4.900	2.900
	0.3	7.700	5.700	4.700	3.700	4.700	5.700	5.700	3.700	4.700	2.700
0	0.5	7.500	5.500	4.500	3.500	4.500	5.500	5.500	3.500	4.500	2.500
	0.7	7.300	5.300	4.300	3.300	4.300	5.300	5.300	3.300	4.300	2.300
	0.9	7.100	5.100	4.100	3.100	4.100	5.100	5.100	3.100	4.100	2.100

(2) Using the range transformation method to standardize the obtained confidence index value and make it

within the scope of [0, 1]. The initial membership function values as shown in Table 6.

Table 6. The initial membership grade of standardized indexes

λ	a	u_1'	v_1'	w_1'	u_2'	v_2'	w_2'	t_2'	u_3'	v_3'	w_3'
	0.1	0.638	0.388	0.263	0.138	0.263	0.388	0.388	0.138	0.263	0.013
	0.3	0.663	0.413	0.288	0.163	0.288	0.413	0.413	0.163	0.288	0.038
1	0.5	0.688	0.438	0.313	0.188	0.313	0.438	0.438	0.188	0.313	0.063
	0.7	0.713	0.463	0.338	0.213	0.338	0.463	0.463	0.213	0.338	0.088
	0.9	0.738	0.488	0.363	0.238	0.363	0.488	0.488	0.238	0.363	0.113
0.5	0~1	0.750	0.500	0.375	0.250	0.375	0.500	0.500	0.250	0.375	0.125
	0.1	0.863	0.613	0.488	0.363	0.488	0.613	0.613	0.363	0.488	0.238
	0.3	0.838	0.588	0.463	0.338	0.463	0.588	0.588	0.338	0.463	0.213
0	0.5	0.813	0.563	0.438	0.313	0.438	0.563	0.563	0.313	0.438	0.188
	0.7	0.788	0.538	0.413	0.288	0.413	0.538	0.538	0.288	0.413	0.163
	0.9	0.763	0.513	0.388	0.263	0.388	0.513	0.513	0.263	0.388	0.138

(3) Using the normalized formula of mutation (table 2) to quantify the recursive calculation of initial membership function value above and get the mutation level of the underlying index values as shown in Table 7.

Table 7. Catastrophe progression of underlying indexes

λ	a	x_{u1}	x_{v1}	x_{w1}	x_{u2}	x_{v2}	x_{w2}	x_{t2}	x_{u3}	x_{v3}	x_{w3}
	0.1	0.798	0.729	0.716	0.371	0.640	0.789	0.827	0.371	0.640	0.334
	0.3	0.814	0.744	0.732	0.403	0.660	0.801	0.838	0.403	0.660	0.440
1	0.5	0.829	0.759	0.748	0.433	0.679	0.813	0.848	0.433	0.679	0.500
	0.7	0.844	0.773	0.762	0.461	0.696	0.825	0.857	0.461	0.696	0.544
	0.9	0.859	0.787	0.776	0.487	0.713	0.836	0.866	0.487	0.713	0.579
0.5	0~1	0.866	0.794	0.783	0.500	0.721	0.841	0.871	0.500	0.721	0.595
	0.1	0.929	0.849	0.836	0.602	0.787	0.885	0.907	0.602	0.787	0.698
	0.3	0.915	0.838	0.825	0.581	0.773	0.875	0.899	0.581	0.773	0.679
0	0.5	0.901	0.825	0.813	0.559	0.759	0.866	0.891	0.559	0.759	0.658
	0.7	0.887	0.813	0.801	0.536	0.744	0.856	0.883	0.536	0.744	0.635
	0.9	0.873	0.800	0.789	0.512	0.729	0.846	0.875	0.512	0.729	0.609

(4) According to catastrophe theory evaluation standards, compute the membership function value of system overall mutation. The non-complementary principle were applied in the primary indexes of evaluation system because of obvious relationship of not compensating each other, and the complementarity principle were applied in the second indexes because of obvious relationship of compensating each other. The results are shown in Table 8.

Table 8. The calculation of final membership grade

λ	a	$x_u=min(x_{u1},x_{v1},x_{w1})$	$x_v=min(x_{u2},x_{v2},x_{w2},x_{t2})$	$x_w=min(x_{u3},x_{v3},x_{w3})$
	0.1	0.716	0.371	*0.334*
	0.3	0.732	0.403	*0.403*
1	0.5	0.748	0.433	*0.433*
	0.7	0.762	0.461	*0.461*
	0.9	0.776	0.487	*0.487*
0.5	0~1	0.783	0.500	*0.500*
	0.1	0.836	0.602	*0.602*
	0.3	0.825	0.581	*0.581*
0	0.5	0.813	0.559	*0.559*
	0.7	0.801	0.536	*0.536*
	0.9	0.789	0.512	*0.512*

(5) In a similar way, process the evaluation data of the miners 2 as mentioned above and get the evaluation results such as Table 9 and shown in figure 2. So, no matter how the value of λ and a change, the evaluation results of miner 1 are between 0.4 and 0.6 and just in the “level I”， that means the emergency ability level is “very poor”. And evaluation results of miners 2 are between 0.062 ~ 0.78, which is in between “level II" and “level III”.

Table 9. The final membership grade of two miners’ emergency response capacity

λ	1					0.5	0				
a	0.1	0.3	0.5	0.7	0.9	0~1	0.1	0.3	0.5	0.7	0.9
x_1	0.334	0.403	0.433	0.461	0.487	0.500	0.602	0.581	0.559	0.536	0.512
x_2	0.622	0.642	0.661	0.680	0.698	0.707	0.783	0.766	0.750	0.733	0.716

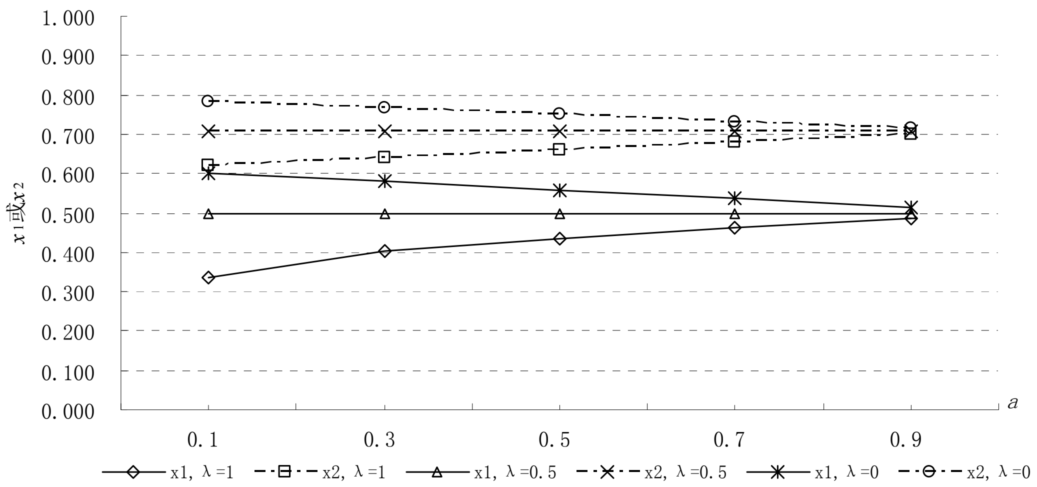

Figure 1. The sketch map of analyzing evaluation results’ solidity

(6) Results analysis. Two miners’ emergency capability evaluation results were basically in accordance with the actual situation through the on-site investigation. And according to the total mutations membership function value of different indexes on the evaluation results for robustness analysis (see Figure 1), found that no matter how change the value of λ and a, the value of the evaluation results was basically in a stable level, indicating the results are steady.

On the basis of the above evaluation method, it not only can compare with the emergency ability of different miners, but also evaluate the different periods’ emergency ability by collecting evaluation data of one miner. We can see the change situation of its emergency ability through the size of the data changes in different periods. If the total mutation membership function of each period is larger and stable, without big fluctuations, we can judge that the level of miners' emergency ability is high. If the total mutation membership function value of each period fluctuates, it indicated that the miners' emergency ability level is not stable, needing some targeted education training. If the emergency ability of the miner's total mutation membership function value in each period remains very low, it indicated the miner’s emergency ability has a lot of problems so that he cannot deal with the emergencies.

5. Discussions

(1) The results of evaluation model of coal miner’s emergency response capacity based on catastrophe theory are close to the actual situation, and can reflect the real problems existing in the evaluation objects. It eliminates the compromise phenomenon between superior index and inferior index in the traditional comprehensive evaluation method. It can effectively identify specific problems and short board existing in the miners' emergency response capability, achieve the scientific evaluation on miners' individual ability on coping with emergencies, and provide the basis for the training of miners’ emergency ability. It has importance for the prevention of coal mine emergencies and reducing accident losses.

(2) Catastrophe theory evaluation model can overcome the disadvantage of traditional evaluation methods in needing to determine the index weight. The model abandoned the difficult issues to obtain index weight, influenced by subjective factors, high uncertainty of evaluation results and so on.

(3) The introduction of the triangular fuzzy number theory to mutation evaluation model can not only preprocess the uncertainty of the underlying index data, but also analyze the robustness of the evaluation results.

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