IJST, Transactions of Civil Engineering, Vol. 38, No. C1, pp 61-73
Printed in The Islamic Republic of Iran, 2014

A RELIABILITY ALLOCATION MODEL AND APPLICATION IN DESIGNING A MINE VENTILATION SYSTEM*

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Abstract– A mine ventilation system is an important component of an underground mining system. It provides a sufficient quantity of air to maintain a suitable working environment. Therefore, the mine ventilation system should be kept at a highly reliable level and also be maintained at a very reliable level during the whole service time of the coal mine. However, in reality, failures of a mine ventilation system do occasionally happen. Most of such failures can result in potential risk for the workers. For example, the insufficient quantity of fresh air to the underground mine working face may lead to the increased concentration of coal gas to the lower flammable limit. Once an ignition source exists, a gas explosion can take place. Hence, some failures become an immediate cause of a mine accident and can cause fatalities and/or property damage. By an in-depth analysis, one of the reasons contributing to the mine ventilation failure is that most systems lack enough technical considerations when they were initially designed. Underestimating the components can substantially lead to a poor quality system. In order to improve coal mine safety, in this paper, a model scientifically allocating the reliability practice is introduced into the mine ventilation systems design process. Such a model can well consider the indeterminate problems in both the decision-making process and the system itself, to achieve the optimum reliability allocation. In detail, first, based on previous research findings, the hierarchical structure of a mine ventilation system is identified by the analytic hierarchy process (AHP) method. Second, the proposed reliability allocation model using the fuzzy mathematics calculation is applied to complete and optimize the reliability allocation works. Application of this model is also demonstrated at the end of this paper.

Keywords– Reliability allocation, design, mine ventilation system

1. INTRODUCTION

Reliability is a popular concept that has been celebrated for years as a commendable attribute of a person or an artifact [1, 2]. Reliability engineering is an engineering field that deals with the study, evaluation, and life-cycle management of reliability [3]. The reliability allocation, as the first step of reliability engineering, deals with the setting of reliability objectives for individual subsystems [4]. In other words, once a specified overall reliability goal for a whole system is determined, the reliability values for each of subsystems must be properly calculated and balanced among themselves. Currently, the reliability allocation has been widely used, such as the mechanical device design [5, 6], computer control [7], electronic components design and optimization [8, 9] so on.

For a mine ventilation system, it is an important component of an underground mining system to provide a sufficient quantity of air to maintain a suitable working environment. In most cases, ventilation is a limiting factor for coal mine production [10]. However, investigation reports of mine fatalities in Chinese coal mines show that defects in the mine ventilation system still exist in some mines and become

*Received by the editors September 6, 2012; Accepted April 23, 2013.
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the root of accidents. It is well known that coal gas explosions present a serious safety threat in the worldwide mining industry. Once, the ventilation system could not deliver enough fresh air into the underground working area and failed to dilute the coal gas. The concentration of gas may build up to reach the lower flammable limit and form explosions. In addition, in some deep coal mines with heat-stress problems, mine ventilation is an effective method for cooling the environment temperature and maintaining suitable working conditions for miners. Also, a good ventilation system can be helpful by preventing coal from spontaneously combusting or a mine fire accident happening. Obviously, the prevention of a mine ventilation system failure is, no doubt, a challenge for mining engineers. But, how to design a successful and reliable mine ventilation system is a complicated task. Technically speaking, a good method to designing the system must consider the relationships between various influencing factors, including difficulties, techniques and economic costs, etc. and also maintaining the system's overall reliability requirement. For years, some researchers conducted studies about reliability design in mining engineering. By analyzing the parameters of Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) for the systems, theoretical probability distribution models are fitted and reliability values, which should be allocated, can be estimated [11]. Kumral [12] converted the reliability allocation of a surface mining system to be a constrained optimization problem and used the Genetic Algorithms (GA) as a tool to solve the problem and achieve the optimal results balancing the desired reliability and the minimum cost. However, this does not completely consider all factors. Such as: complexity of system, related work environment, etc. For a mine's ventilation system, Wang [13] developed a bottom-up approach to carry out the reliability allocation. The most frequently damaged elements are put in the very first place for designing. Then, based on that, the subsystems can be designed until the whole system works. Apparently, this method can greatly improve the system's reliability, but the cost may be unacceptable.

Mathematically speaking, the reliability allocation can be expressed in Eq. (1)

$$\begin{cases} R_S(R_1, R_2, \cdots R_i, \cdots R_n) \geq R_S^* \\ \vec{g}_S(R_1, R_2, \cdots R_i, \cdots R_n) < \vec{g}_S^* \end{cases} \tag{1}$$

Where R_s is the reliability index of a mine ventilation system;

R_S^* is the expected reliability value of a mine ventilation system;

$\vec{g}_s$ is the constraint condition of a mine ventilation system design;

$\vec{g}_s^*$ is the maximum constraint condition of a mine ventilation system design;

R_i is the reliability index of the "i" th subsystem.

In this paper, a model of the reliability allocation is presented. This model not only can complete the allocation but also can optimize the distributions of reliability goals for each subsystem considering various influencing factors. A case demonstration is shown at the end of this paper.

2. ANALYSIS OF A MINE VENTILATION SYSTEM

a) Subsystems of a mine ventilation system

Generally, there are various models of mine ventilation systems due to different geological conditions, production rates, mining laws and regulations, etc. However, the basic subsystems in a mine ventilation system are still the same. Therefore, based on an in-depth analysis of the functions of a mine ventilation system, the following six subsystems are classified to constitute a mine ventilation system:

(A) The subsystem of mine ventilation power: the aim of a mine ventilation system is to supply sufficient air into to the underground and to create a suitable working environment. Hence, the mine's main fan, as the only component in this subsystem, plays a very important role. Its reliability can directly determine the success or failure of a mine ventilation system.

(B) The subsystem of mine ventilation network structure and its pattern: along with coal mine production, changes to mining areas and developments of mine entries, etc. keep happening all the time. Accordingly, the mine ventilation network cannot be the same at any one point in time, therefore, mining operators must adjust the air distributions in the underground to keep a suitable environment. However, an unexpected unsteady airflow may result in a mine accident and also can spread its hazards in a short time due to air movements. Accordingly, it is required that a simple but powerful design to control the mine ventilation network structure should be designed at the beginning.

(C) The subsystem of ventilation facilities in a mine ventilation system: in addition to the mine ventilation network and the mine's main fan, ventilation facilities are also very important to realize the functions of a mine ventilation system. Facilities including doors, curtains and seals, etc. that can guide the airflow direction; control air leakages; and make sure a sufficient air quantity can be delivered to the underground working areas.

(D) The subsystem of mine atmosphere monitoring: Due to the complicated underground environment, mining engineering is considered a high-risk industry. Therefore, monitoring devices are needed to keep safety levels high. Mine operators can successfully track some critical environmental parameters as well as their changes over the time. These parameters include concentrations of methane, carbon monoxide, carbon dioxide and oxygen, temperature, air velocity, atmospheric pressure and so on. The ventilation system is a dynamic system which induces the probability of risk factors making system failures randomly. Hence, a mine atmosphere monitoring subsystem is needed and is also an effective measure to detect any accidents.

(E) The subsystem of disaster prevention facilities: a ventilation system can not only provide fresh air during a coal mine normal production life but also does it when an accident happens. A qualified disaster prevention facilities subsystem should include: (1) Mine fire prevention facilities. Coal mine fire, is a major accident threatening miners' safety. Hence, fire prevention facilities are necessary. (2) Dust-proof facilities. With the popularization of mechanization of coal mining, the dust generation is increased greatly and gradually becomes a limiting factor for production. (3) Water-proof facilities. Underground mine water is also a source of danger in mines. According to statistics, huge economic losses, caused by mine water, are very common. (4) Gas control and drainage facilities. Coal mine gas is the most hazardous gas in the underground. Mine gas explosions can kill a large number of miners in a very short time. Therefore, coal gas control or its drainage is mandatory for some mines, especially for gassy mines.

(F) The subsystem of ventilation management: A good ventilation system not only includes high quality equipment but also an effective management regulation that makes sure the system is running safely.

b) Factors that affect mine ventilation system design

The influencing factors can be classified into the following types:

A) Technique ability: Different units have different design techniques. For a unit with a proven technology or an advanced production technology, a high reliability value is necessary or if the reliability is expected to increase after putting it into use, a large value should be assigned.

B) Complexity: Basically speaking, the complexity depends on the number of basic components needed to constitute a functional subsystem as well as the difficulty in assembling. For instance, if the subsystem is so complicated that several units are needed to assemble it. Thus, a great reliability value should be assigned. Conversely, if the subsystem is simple and easy to be maintained a small reliability value can be given. It should be noted that although a subsystem is initially considered a "simple" subsystem due to its small number of units; it should be treated as a complicated subsystem when it needs a long assembly time.

C) Importance: Whether a subsystem is functional or not is significant for the failure of the whole mine ventilation system. For instance, if a certain unit fails and the consequences are serious, such as the whole system is totally down, this unit can be considered very important. However, if the failed unit can only cause part of the functions of the system to shut down, this unit has less importance.

D) Economic: In general, there is an exponential relationship between the system safety level and its corresponding investment. When the safety level is poor, a small amount of safety investment can greatly improve it. However, there is an optimal point which means both the increasing rate of safety level and the investment efficiency are at maximum. In other words, after this point, more capital investment is needed to keep the current safety level. However, the funding for a mining company is not unlimited. Therefore, it is important to find a balance between capital investment and safety.

E) Task: This factor can be reflected in the two following aspects: working time and working environment. The working time refers to how long a unit should work. If continuous work is needed, a small reliability value should be assigned to such units. On the other hand, a high reliability value should be given to temporary, short-term work units. The working environment refers to external conditions. Some units are in poor working condition and they are hard to maintain with a high reliability. Therefore, a small reliability value should be assigned. If the working conditions are good and the units are easy to repair, a greater reliability value can be given.

3. PROPOSED RELIABILITY ALLOCATION MODEL

The authors have developed a new allocation model by combining the analytic hierarchy process (AHP) method and the fuzzy mathematical calculation. In general, the analytic hierarchy process (AHP) method is used to establish the structure of a mine ventilation system while the fuzzy theory is applied to carry out the reliability allocation. The procedure is shown as follows:

- **Establish the analytic hierarchy structure for a ventilation system:**

Based on the previous analyses of a mine ventilation system's functions and the related influence factors, the Analytic Hierarchy Process (AHP) method is a well approved approach to establish the analytic hierarchy structure of a ventilation system [14, 15]. Basically speaking, there are three different levels in the structure, which are the goal level, the criteria level and the alternatives level, respectively. The goal level is the global reliability of a mine ventilation system. The criteria level consists of subsystems in a ventilation system as stated in the last section. The alternatives level, mainly refers to the influence factors that can affect the systems design. Figure 1 shows the analytical structure.

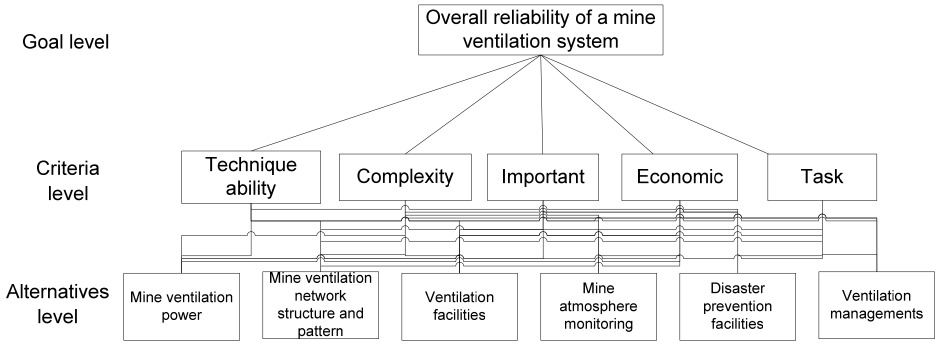

Fig. 1. Schematic for analytical structure using the AHP method

- **Determine the evaluation set and scale**

In this research effort, the evaluation set is designed as five grades. Hence, the evaluation scale also has five characteristic numbers. Generally, the numbers 1, 3, 5, 7 and 9 are used to represent each of the grades. For any one of these factors, due to different physical meanings, different descriptions are made for the evaluation set. For example, the evaluation set is defined as: not mature, fair mature, medium mature, mature, high mature, for the factor of technique ability, while the set is defined as: not important, fair important, medium important, important, very important, for the factor of importance. Table 1 lists the detailed definitions.

Table 1. Definitions and meanings for fuzzy assessment sets

Scale	Definitions					
	Meanings	Technique ability	Complexity	Important	Economic	Task
1	Not important	Not mature	Very Complicated	Not important	Very small	Not important
3	Fair important	Fair mature	Complicated	Fair important	Small	Fair important
5	Medium important	Medium mature	Medium Complicated	Medium important	Fair small	Medium important
7	Important	Mature	Simple	Important	General	Important
9	Very important	High mature	Very Simple	Very important	High	Very important

- **Determine fuzzy weighting assessment vector**

Considering effects by weightings, the matrix of weighting assessment vector to a specified factor in the criteria level can be written as:

$$\bar{W} = \{\overline{w_1}, \overline{w_2}, \overline{w_3}, \overline{w_4}, \overline{w_5}\}^T \tag{2}$$

Where: $\overline{w_n}(i = 1, 2...5)$ is the weighting for each influencing factor.

- **Establish fuzzy assessment matrix**

For a subsystem in the alternatives level, the fuzzy assessment of it to each of the influencing factors should be done first. Therefore, for the subsystem "i", a fuzzy assessment row vector $\tilde{C}_i$ can be expressed as:

$$\tilde{C}_i = \{\tilde{c}_{i1}, \tilde{c}_{i2}, \tilde{c}_{i3}, \tilde{c}_{i4}, \tilde{c}_{i5}\} \qquad i = 1, 2, ..., 6 \tag{3}$$

Where, $\tilde{c}_{ij}(i = 1, 2, ..., 6; j = 1, 2, ..., 5)$ means the assessment value for a specified subsystem "i" with respect to the particular factor j.

Accordingly, a group of assessment row vectors can be combined to give the fuzzy assessment matrix:

$$\tilde{C}=\begin{bmatrix}\tilde{C}_1\\ \tilde{C}_2\\ \vdots\\ \tilde{C}_6\end{bmatrix}=\begin{bmatrix}\tilde{c}_{11} & \tilde{c}_{12} & \cdots & \tilde{c}_{15}\\ \tilde{c}_{21} & \tilde{c}_{22} & \cdots & \tilde{c}_{25}\\ \vdots & \vdots & \ddots & \vdots\\ \tilde{c}_{61} & \tilde{c}_{62} & \cdots & \tilde{c}_{65}\end{bmatrix} \tag{4}$$

Calculate cut set under α level for assessment vector

First of all, the new variable, the triangular fuzzy number, needs to be introduced. Essentially, the triangular fuzzy number can also be considered as a membership function; it can convert a certain value into different membership values projected on different ranges to finish the fuzzification. The triangular fuzzy number can be expressed as:

$$\tilde{x}=(a_1,a_2,a_3) \tag{5}$$

Its corresponding membership function is

$$\mu_A(x)=\begin{cases}0 & x<a_1\\ \dfrac{x-a_1}{a_2-a_1} & a_1\le x\le a_2\\ \dfrac{a_3-x}{a_3-a_2} & a_2\le x\le a_3\\ 0 & x>a_3\end{cases}$$

According to the evaluation scale mentioned before, characteristic values to the triangle fuzzy number can be written as:

Table 2. Characteristic values for triangle fuzzy numbers

Triangle fuzzy number	Characteristic values		
	a_1	a_2	a_3
1	1	1	3
$\tilde{x}(x=3,5,7)$	$x-2$	x	$x+2$
9	7	9	9

A fuzzy value's α cut set can be obtained once the membership value of α is given. Figure 2 shows the mathematical meaning of α cut set. For ∀ $\alpha\in[0,1]$, the fuzzy value can be calculated as:

$$\tilde{x}^{\alpha}=[x_l^{\alpha},x_u^{\alpha}]=[(a_1-a_2)\alpha+a_1,-(a_3-a_2)\alpha+a_3] \tag{7}$$

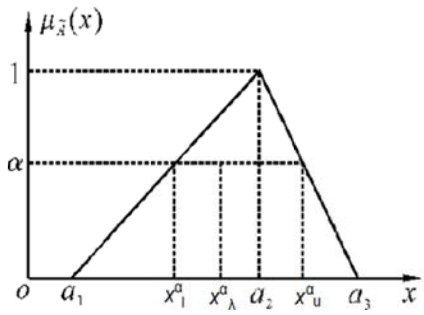

Fig. 2. Mathematical meanings of cut set α

α reflects the system's fuzzy degree. A big value of α means the system has less fuzziness. When $\alpha = 1$, it is a non-fuzzy system.

Based on the definition of α cut set, Eq. (2) and Eq. (4) can be rewritten with corresponding α cut set as:

$$\tilde{W}^{\alpha} = \{\overline{w_1^{\alpha}}, \overline{w_2^{\alpha}}, \overline{w_3^{\alpha}}, \overline{w_4^{\alpha}}, \overline{w_5^{\alpha}}\}^T \tag{8}$$

Where $\overline{w_i^{\alpha}} = [w_{il}^{\alpha}, w_{iu}^{\alpha}], (i = 1, 2...5)$

$$\tilde{C}^{\alpha} = \begin{bmatrix} \tilde{C}_1^{\alpha} \\ \tilde{C}_2^{\alpha} \\ \vdots \\ \tilde{C}_6^{\alpha} \end{bmatrix} = \begin{bmatrix} \tilde{c}_{11}^{\alpha} & \tilde{c}_{12}^{\alpha} & \cdots & \tilde{c}_{15}^{\alpha} \\ \tilde{c}_{21}^{\alpha} & \tilde{c}_{22}^{\alpha} & \cdots & \tilde{c}_{25}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{c}_{61}^{\alpha} & \tilde{c}_{62}^{\alpha} & \cdots & \tilde{c}_{65}^{\alpha} \end{bmatrix} \tag{9}$$

Where $\tilde{c}_{ij}^{\alpha} = [c_{ijl}^{\alpha}, c_{iju}^{\alpha}](i = 1, 2, ..., 6; j = 1, 2, ..., 5)$

- **Determine fuzzy comprehensive assessment matrix:**

The fuzzy comprehensive assessment matrix can be determined by using products of $\tilde{c}_{ij}^{\alpha}$ and $\overline{w_i^{\alpha}}$ as:

$$\overline{A^{\alpha}} = \begin{bmatrix} \tilde{a}_{11}^{\alpha} & \tilde{a}_{12}^{\alpha} & \cdots & \tilde{a}_{15}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & \tilde{a}_{22}^{\alpha} & \cdots & \tilde{a}_{25}^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{61}^{\alpha} & \tilde{a}_{62}^{\alpha} & \cdots & \tilde{a}_{65}^{\alpha} \end{bmatrix} = \begin{bmatrix} \tilde{c}_{11}^{\alpha} \otimes \overline{w}_1^{\alpha} & \tilde{c}_{12}^{\alpha} \otimes \overline{w}_2^{\alpha} & \cdots & \tilde{c}_{15}^{\alpha} \otimes \overline{w}_5^{\alpha} \\ \tilde{c}_{21}^{\alpha} \otimes \overline{w}_1^{\alpha} & \tilde{c}_{22}^{\alpha} \otimes \overline{w}_2^{\alpha} & \cdots & \tilde{c}_{25}^{\alpha} \otimes \overline{w}_5^{\alpha} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{c}_{61}^{\alpha} \otimes \overline{w}_1^{\alpha} & \tilde{c}_{62}^{\alpha} \otimes \overline{w}_2^{\alpha} & \cdots & \tilde{c}_{65}^{\alpha} \otimes \overline{w}_5^{\alpha} \end{bmatrix}_{6\times 5} \tag{10}$$

Where: $\otimes$ is fuzzy operator and $\tilde{a}_{ij}^{\alpha} = [a_{ijl}^{\alpha}, a_{iju}^{\alpha}] = \tilde{c}_{ij}^{\alpha} \otimes \tilde{w}_j^{\alpha} = [c_{ijl}^{\alpha} \times w_{jl}^{\alpha}, c_{iju}^{\alpha} \times w_{ju}^{\alpha}]$

- **Calculate fuzzy comprehensive assessment matrix' s λ cut set**

Defining optimistic index λ (λ∈[0,1])) and taking operations for Eq(7), non-fuzzy number of $\tilde{x}^{\alpha}$ can be calculated as:

$$\hat{x}_{\lambda}^{\alpha} = x_l^{\alpha} + \lambda(x_u^{\alpha} - x_l^{\alpha}) \tag{11}$$

A large optimistic index λ can induce a large non-fuzzy number. When $\lambda = 1$, $\hat{x}_{\lambda}^{\alpha} = x_u^{\alpha}$ .On the other hand, λ can be used to indicate the degree of satisfaction of matrix A^{α} and converts A^{α} into a non-fuzzy matrix A_{λ}^{α} :

$$A_{\lambda}^{\alpha} = \begin{bmatrix} \hat{a}_{11} & \hat{a}_{12} & \cdots & \hat{a}_{15} \\ \hat{a}_{21} & \hat{a}_{22} & \cdots & \hat{a}_{25} \\ \vdots & \vdots & & \vdots \\ \hat{a}_{61} & \hat{a}_{62} & \cdots & \hat{a}_{65} \end{bmatrix}_{6\times 5} \tag{12}$$

Where: $\hat{a}_{ij} = \lambda a_{iju}^{\alpha} + (1-\lambda) a_{ijl}^{\alpha} \qquad (i = 1, 2, ..., 6; j = 1, 2, ..., 5)$

- **Calculate Entropy weight**

Normalizing the matrix A_{λ}^{α} **to yield:**

$$F=\begin{bmatrix} f_{11} & f_{12} & \cdots & f_{15} \\ f_{21} & f_{22} & \cdots & f_{25} \\ \vdots & \vdots & & \vdots \\ f_{61} & f_{62} & \cdots & f_{65} \end{bmatrix}=\begin{bmatrix} \hat{a}_{11}/s_1 & \hat{a}_{12}/s_1 & \cdots & \hat{a}_{15}/s_1 \\ \hat{a}_{21}/s_2 & \hat{a}_{22}/s_2 & \cdots & \hat{a}_{25}/s_2 \\ \vdots & \vdots & & \vdots \\ \hat{a}_{61}/s_6 & \hat{a}_{62}/s_6 & \cdots & \hat{a}_{65}/s_6 \end{bmatrix} \tag{13}$$

Where: $s_k=\sum_{j=1}^{5}\hat{a}_{kj}\,(k=1,2,...,6)$

$f_{ij}\,(i=1,2,...,6;\,j=1,2,...,5)$ stands for the weighting factor for the specified subsystem “”i" with respect to the particular factor “j”.

On the other hand, the vector of entropy weight can be defined as:

$$H=[h_1 \quad h_2 \quad \cdots \quad h_i]^T \tag{14}$$

According to the definition in informatics science, the value of entropy weight is defined as:

$$h_i=-\sum_{j=1}^{6} f_{ij}\log(f_{ij}),(i=1,2,...,6;\,j=1,2,...,5) \tag{15}$$

A great value of entropy weight shows that the system has strong closure and it is not easily disturbed by external effects.

- **Reliability allocation calculation**

Assuming the reliability values for subsystems are $R_1, R_2, ..., R_6$ to give:

$$R_i=\frac{h_i}{h_1}R_1,(i=1,2,...,6) \tag{16}$$

On the other hand, assuming the global reliability value for a mine system is R_s, for a serial system, the following equation is given:

$$R_s=\prod_{i=1}^{6}R_i=\left(\frac{R_1}{h_1}\right)^6\bullet\prod_{i=1}^{6}h_i,(i=1,2,...,6) \tag{17}$$

Therefore, the reliability allocation for each subsystem can be calculated by the following system of equations:

$$\begin{cases} R_1=\left(R_s/\prod_{i=1}^{6}h_i\right)^{1/6}\bullet h_1 \\ R_k=\frac{h_k}{h_1}R_1=h_k\bullet\left(R_s/\prod_{i=1}^{6}h_i\right)^{1/6} \end{cases} \quad k=(2,3,...,6) \tag{18}$$

4. CASE DEMONSTRATION

A coal mine located in the northern part of China is going to be designed. As a consolidation effort, the reliability allocation for the mine ventilation system should be done in order to improve the coal mine safety. Base on the reality, the assessment results for each subsystem are collected. Table 3 lists the results.

Table 3. Values of Influencing factors for different subsystems

Subsystem	Influence factors				
	Technique ability	Complexity	Important	Economic	Task
Mine ventilation power	Mature	Very Complicated	Fair important	General	Medium important
Network structure and pattern	High mature	Complicated	Medium important	General	Important
Facilities	Mature	Complicated	Fair important	General	Important
Mine atmosphere monitoring	Mature	Very Complicated	Fair important	General	Medium important
Disaster prevention facilities	High mature	Complicated	Important	General	Medium important

According to Table 3, the fuzzy assessment matrix can be generated as:

$$\tilde{C} = \begin{bmatrix} 7 & 1 & 3 & 5 & 5 \\ 9 & 3 & 5 & 5 & 7 \\ 7 & 3 & 3 & 5 & 7 \\ 7 & 1 & 3 & 5 & 5 \\ 9 & 3 & 7 & 5 & 5 \\ 9 & 3 & 5 & 5 & 7 \end{bmatrix} \tag{19}$$

The five influencing factors considered in this designing are: technique ability, complexity, importance, economy and task. The weighting assessment vector is defined as: important, important, very important, important, very important, which are represented by numbers, like:

$$\tilde{W} = \{7,7,9,7,9\}^T \tag{20}$$

Given the global reliability value of 0.85 for the whole mine ventilation system and finishing the calculation followed by Eq (5) to Eq (18), Table 4 gives out the reliability allocation results under different combinations of λ and α .

Table 4. Results of MVS reliability allocations

λ		α								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	R_1	0.94900	0.94966	0.95020	0.95055	0.95056	0.94993	0.94799	0.94172	0.93738
	R_2	0.98433	0.98487	0.98591	0.98773	0.99079	0.99601	0.99653	0.99736	0.99862
	R_3	0.95600	0.95023	0.94298	0.93365	0.92134	0.90443	0.87979	0.83837	0.76756
	R_4	0.98237	0.98602	0.98989	0.99391	0.99787	0.99802	0.99852	0.99665	0.98706
	R_5	0.98433	0.98487	0.98591	0.98773	0.99079	0.99601	0.99721	0.99836	0.99906
	R_6	0.98433	0.98487	0.98591	0.98773	0.99079	0.99601	0.99721	0.99836	0.99906
0.2	R_1	0.97037	0.97085	0.97589	0.97578	0.97879	0.98374	0.98632	0.99368	0.96941
	R_2	0.97943	0.98071	0.97847	0.97900	0.98022	0.97933	0.97964	0.97894	0.99979

	R_3	0.96078	0.95608	0.95276	0.95141	0.94203	0.93513	0.92935	0.91760	0.90506
	R_4	0.97037	0.97085	0.97589	0.97578	0.97879	0.98374	0.98632	0.99368	0.96941
	R_5	0.97943	0.98071	0.97847	0.97900	0.98022	0.97933	0.97964	0.97894	0.99979
	R_6	0.97943	0.98071	0.97847	0.97900	0.98022	0.97933	0.97964	0.97894	0.99979
0.3	R_1	0.96963	0.96712	0.96905	0.96732	0.97229	0.97443	0.97624	0.97309	0.98001
	R_2	0.97842	0.98051	0.97968	0.98165	0.97918	0.97992	0.97965	0.98263	0.98031
	R_3	0.96523	0.96406	0.96265	0.96031	0.95773	0.95136	0.94862	0.94612	0.93942
	R_4	0.96963	0.96712	0.96905	0.96732	0.97229	0.97443	0.97624	0.97309	0.98001
	R_5	0.97842	0.98051	0.97968	0.98165	0.97918	0.97992	0.97965	0.98263	0.98031
	R_6	0.97842	0.98051	0.97968	0.98165	0.97918	0.97992	0.97965	0.98263	0.98031
0.4	R_1	0.96541	0.96705	0.96590	0.96836	0.96694	0.96979	0.96874	0.96724	0.96664
	R_2	0.97999	0.97944	0.98062	0.97925	0.98080	0.97945	0.98023	0.98252	0.98317
	R_3	0.96901	0.96738	0.96615	0.96532	0.96356	0.96188	0.96168	0.95790	0.95719
	R_4	0.96541	0.96705	0.96590	0.96836	0.96694	0.96979	0.96874	0.96724	0.96664
	R_5	0.97999	0.97944	0.98062	0.97925	0.98080	0.97945	0.98023	0.98252	0.98317
	R_6	0.97999	0.97944	0.98062	0.97925	0.98080	0.97945	0.98023	0.98252	0.98317
0.5	R_1	0.96341	0.96251	0.96376	0.96374	0.96430	0.96619	0.96485	0.96433	0.96473
	R_2	0.98087	0.98118	0.98075	0.98058	0.98081	0.97979	0.98107	0.98134	0.98249
	R_3	0.97043	0.97131	0.97008	0.97062	0.96882	0.96804	0.96692	0.96720	0.96299
	R_4	0.96341	0.96251	0.96376	0.96374	0.96430	0.96619	0.96485	0.96433	0.96473
	R_5	0.98087	0.98118	0.98075	0.98058	0.98081	0.97979	0.98107	0.98134	0.98249
	R_6	0.98087	0.98118	0.98075	0.98058	0.98081	0.97979	0.98107	0.98134	0.98249
0.6	R_1	0.96230	0.96068	0.96262	0.96374	0.96210	0.96343	0.96220	0.96371	0.95827
	R_2	0.98108	0.98210	0.98079	0.98038	0.98111	0.98066	0.98130	0.98089	0.98370
	R_3	0.97204	0.97229	0.97225	0.97122	0.97235	0.97100	0.97159	0.96975	0.97242
	R_4	0.96230	0.96068	0.96262	0.96374	0.96210	0.96343	0.96220	0.96371	0.95827
	R_5	0.98108	0.98210	0.98079	0.98038	0.98111	0.98066	0.98130	0.98089	0.98370

	R_6	0.98108	0.98210	0.98079	0.98038	0.98111	0.98066	0.98130	0.98089	0.98370
0.7	R_1	0.96080	0.95991	0.95950	0.96121	0.95965	0.95923	0.96012	0.95684	0.95776
	R_2	0.98163	0.98211	0.98240	0.98121	0.98222	0.98225	0.98197	0.98398	0.98332
	R_3	0.97345	0.97381	0.97379	0.97385	0.97401	0.97478	0.97381	0.97449	0.97459
	R_4	0.96080	0.95991	0.95950	0.96121	0.95965	0.95923	0.96012	0.95684	0.95776
	R_5	0.98163	0.98211	0.98240	0.98121	0.98222	0.98225	0.98197	0.98398	0.98332
	R_6	0.98163	0.98211	0.98240	0.98121	0.98222	0.98225	0.98197	0.98398	0.98332
0.8	R_1	0.95998	0.96045	0.95952	0.95801	0.95904	0.95723	0.95505	0.95617	0.95522
	R_2	0.98191	0.98153	0.98202	0.98286	0.98208	0.98319	0.98436	0.98351	0.98441
	R_3	0.97427	0.97444	0.97489	0.97545	0.97567	0.97606	0.97701	0.97726	0.97652
	R_4	0.95998	0.96045	0.95952	0.95801	0.95904	0.95723	0.95505	0.95617	0.95522
	R_5	0.98191	0.98153	0.98202	0.98286	0.98208	0.98319	0.98436	0.98351	0.98441
	R_6	0.98191	0.98153	0.98202	0.98286	0.98208	0.98319	0.98436	0.98351	0.98441
0.9	R_1	0.96028	0.95990	0.96031	0.95874	0.95746	0.95630	0.95589	0.95677	0.95280
	R_2	0.98171	0.98168	0.98132	0.98220	0.98286	0.98316	0.98335	0.98291	0.98488
	R_3	0.97425	0.97512	0.97535	0.97593	0.97658	0.97805	0.97833	0.97784	0.98009
	R_4	0.96028	0.95990	0.96031	0.95874	0.95746	0.95630	0.95589	0.95677	0.95280
	R_5	0.98171	0.98168	0.98132	0.98220	0.98286	0.98316	0.98335	0.98291	0.98488
	R_6	0.98171	0.98168	0.98132	0.98220	0.98286	0.98316	0.98335	0.98291	0.98488

Note: $R_1 \ldots R_6$ represent the subsystem in a mine ventilation system and also follow the order stated in the previous section.

Essentially speaking, the fuzziness during the process of reliability allocation for a mine ventilation system can be understood by the following two aspects: Firstly, the fuzziness of the system itself. The cut set α can reflect the system's fuzzy degree. A great value of α means the system has small fuzziness and clear concepts and boundaries. Secondly, the fuzziness that a decision-maker has during the process of designing a mine ventilation system can be reflected by the cut set λ. The bigger the λ is, the greater the uncertainty is made in the decision-making process. Therefore, Table 4 provides assigned reliable allocations under various conditions of decision-making, different subsystems and fuzzy degrees. In an actual design, the table above can be consulted to determine proper reliable values and improve the design quality based on the mine's reality.

In accordance with the practice of engineering design, project designers consist of global designers and systemic designers. Hence, reliability analysts also consist of both global reliability analysts and systemic reliability analysts. In the process of establishing a model, the global reliability analysts are responsible for establishing the global-level reliability model while the systemic reliability analysts are in charge of the establishment of a system-level model. The so-called global-level model can reflect the failure laws of a mine ventilation system, and the system-level model can reflect reasons that result in one subsystem failure. From the view of model structure, the system-levels model can be considered as modules of the global-level model. Therefore, the global-level model is the key to a good system design. A mine ventilation system is actually a giant complicated system. Although there are different components that go into making up the subsystems, the main categories of subsystems do not change much. Thus, the global-level model has better versatility.

On the other hand, due to the different mining conditions of mines, the design of subsystems may vary. The case demonstration gives out the reliability allocations for the most versatile six subsystems on a global level based on different combinations of α and λ. In addition, once a subsystem's reliability allocation is chosen, the proposed model can also be used to determine the expected reliability values for the next lower subsystems until designed for specified component units.

5. CONCLUSION

The mine ventilation system plays an important role in an underground mining system. In order to improve mine safety, this paper presents a new reliability allocation model which can well balance the various influencing factors, such as unit importance, task, economy, and so on, in designing a mine ventilation system. Based on an in-depth analysis of the mine ventilation system's structure, a mathematical model combining the analytic hierarchy process (AHP) and the fuzzy calculation theory has been developed to carry out the reliability allocation for each subsystem. The solutions that are derived by the developed model are more accurate and scientific. Therefore, the allocation procedure of this model would ensure that the designed mine ventilation system is the more reasonable and has higher engineering quality. In addition, this model can also help the designers to continue the reliability allocation within the lower subsystem. The case demonstration shows the allocation results of the top subsystems for a mine ventilation system. These could be applied as guidelines in mine design practices.

Acknowledgements: This work is financially supported by grants from the Fundamental Research Funds for Central Universities (Grant No. 2013QNA01), the National Science Foundation of China (Grant No.51304203) and the Natural Science Foundation of Jiangsu Province of China for Youths (Grant No. BK20130191); the authors are grateful for these supports.

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