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A model of unsafe behavior in coal mines based on game theory

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ABSTRACT

Behavior choice, coal mine monitoring, and control intensity are combined in a general mathematical model established from the perspective of a behavioral game. A case study is provided with effective conditions of monitoring provided. This paper defines the expected value difference of control return and behavior cost difference and discusses the measurement and optimization of variable indexes, including the monitoring intensity and costs of control. The results imply that the control of unsafe behavior can be more effective when monitoring and control of coal mines are both improved. Monitoring will be useful when the rewards for displaying safe behavior, and the monitoring of unsafe behavior, are improved to a high level.

1. Introduction

Compared to developed countries the safety situation in Chinese coal mines is still unsatisfactory. This is despite increasingly safe production and fewer accidents and casualties. In fact statistics from coal mine accident investigations show that in China over 80% of the accidents result from direct or indirect behavior of the staff. Coal mine accidents can be reduced through prevention and control of unsafe behaviors.

Foreign scholars have studied unsafe human behavior earlier than those in China. In 1919, M Greenwood and H H Woods first started the qualitative study of unsafe behavior through statistical tests on accident occurrences. Their study examined different statistical distributions. The results showed that accidents happen more often with some of the workers. After the end of the 20th century, foreign studies on factors influencing individual safe behavior advanced. Jane Mullen conducted a qualitative study on these influencing factors and presented organizational and social factors related to an individual's engagement in dangerous work [1]. Hofmann and Stitzer thought that working pressure, resulting from overwork, could influence safe behavior and that insufficient working hour, training, and resources could influence job performance [2].

Laboratory equipment and experimental methods for the study of human factors in China is relatively backward compared to foreign studies. However, since the 1980's Chinese scholars have been doing more studies on human factors and have made some remarkable achievements. Lin Zeyan discovered that accidents and death tollscaused by human adventure both exceeded those caused by unexpected accidents [3]. This was true in state coal mines, in state owned local mines, or in township mines [3]. Cheng Weimin and Zhou Gang thought human unsafe behavior should be controlled from three aspects: establishing and maintaining an operator's interest in safe work, job standardization, and safety management [4]. Mi Chuming determined the coal mine, personnel accident cause analysis frame leading to a three level prevention scheme consisting of organization, work team, and the individual. They constructed the correction model of human errors in coal mine accidents [5].

Despite the great value of the above mentioned studies they have only laid importance to the study of specific unsafe behavior monitoring strategies. This results in insufficient quantitative study from the perspective of microscopic mechanisms. A general mathematical model of coal miners' unsafe behavior has been established from the perspective of behavioral game theory to find new ways of quantitatively studying coal mine safety management practice. This model is based on the above discussion and uses a relative theoretical model for reference [6,7]. It refers to staff choice in behavior, coal mine monitoring, and control intensity.

2. Principles of an unsafe behavior monitoring mechanism

2.1. Basic concepts

Suppose there are two kinds of coal miner behaviors. They are: a_1 representing unsafe behavior, which is prohibited by coal mine

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Table 1
Game rules of the unsafe behavior monitoring scheme.

Conditional probability value	Meaning
$p(w(a_i)/a_i) = p_a(a_i)$	Natural return $w(a_i)$ occurs with certain probability.
$p(-c(a_i)/a_i) = 1$	Relevant cost occurs definitely when coal miner chooses and realizes any behavior, and there always exists $c(a_2) > c(a_1)$.
$p(v(a_1)/a_1) = p_b(a_1)p_d(a_1)$	Coal miner's control return is related to the monitoring intensity and control intensity.
$p(v(a_2)/a_1) = [1 - p_b(a_1)]p_d(a_2)$	The default result would be safe when they chose unsafe behavior in case of no
$p(v(a_2)/a_2) = p_d(a_2)$	monitoring. $v(a_1) < 0, v(a_2) \geqslant 0$.

safety and operating rules; and, a_2 representing safe behavior, which complies with the rules and is encouraged by the enterprise.

Generally speaking, three kinds of results are to be considered: (1) behavior cost, $c(a_i)$, represent physical consumptions when the behavior is carried out; (2) behavior monitoring cost, $v(a_i)$, represents rewards and punishments from the enterprise; and, (3) natural return, $w(a_i)$ results from general rules and involves such things as extra economic income or physical saving resulting from unsafe behavior. Of course, safe behavior can help individuals and companies win positive evaluations and safety reward [8,9].

Suppose $p_b(a_i)$ is the monitoring intensity of a coal miner's behavior and $p_d(a_i)$ is the control intensity. Enough economic and labor costs are put into behavior monitoring. Once behavior a_i occurs, cost $c(a_i)$ occurs so then the probability of cost occurrence is always 1. However, the control return $v(a_i)$ is related to monitoring intensity and control intensity so the natural return occurs according to some probability distribution describing behavior choices.

2.2. Game rules of the unsafe behavior monitoring mechanism

The following clarifies the game rules between the coal mine and its staff in terms of unsafe behavior monitoring mechanisms.

When staff behavior is incompletely observed in the coal mine monitoring intensity is characterized as a probability, $p_b(a_i)$. The management cost control and activity level is characterized by $p_d(a_i)$. When the coal miner chooses behavior a_1 management controls the return to the coal miner, $v(a_1)$, in proportion to $p_d(a_1)$. The return is 0 when the control is not carried out. When the miner's choice, a_1, belongs to the class of unsafe behavior a_1 the coal mine will regard safe behavior as the default result and give a return to the coal miner of $v(a_1)$ by $p_d(a_2)$. There is zero return for zero control. When the coal miner chooses behavior a_2 the corresponding return is $v(a_2)$ by $p_d(a_2)$ and the return is zero when the control is not carried out. When the monitoring is free, behavior is thought to be safe and the return to the coal miner is $v(a_2)$ by $p_d(a_2)$ and zero return is for zero control.

Suppose the monitoring cost is c_b and that the cost of returns provided to employees $v(a_1)$ and $v(a_2)$ are given as cost $v(a_1,a_2)$. Now $c_b + c_v(a_1,a_2)$ is the total cost of conducting the monitoring scheme [10–12].

From the coal miner perspective their choice of unsafe behavior, a_1, gives a natural return $w(a_1)$ by the probability $p_a(a_1)$. Their control return is:

$$p_b(a_1)p_d(a_1)v(a_1) + [1 - p_b(a_1)]p_d(a_2)v(a_2) = p_d(a_1)v(a_1) + [1 - p_b(a_1)][p_d(a_2)v(a_2) - p_d(a_1)v(a_1)].$$

If their choice is the safe behavior, a_2, they get the natural return $w(a_2)$ by the probability $p_a(a_2)$ and their control return is:

$$p_b(a_2)p_d(a_2)v(a_2) + (1 - p_b(a_2))p_d(a_2)v(a_2) = p_d(a_2)v(a_2)$$

Certainly, coal miners need to spend relevant costs while making their choices and realizing them. Suppose $c(a_1)$ is the cost of unsafe behavior a_1 and $c(a_2)$ is the cost of safe behavior a_2. Given all this, the probability of the various returns is listed in Table 1.

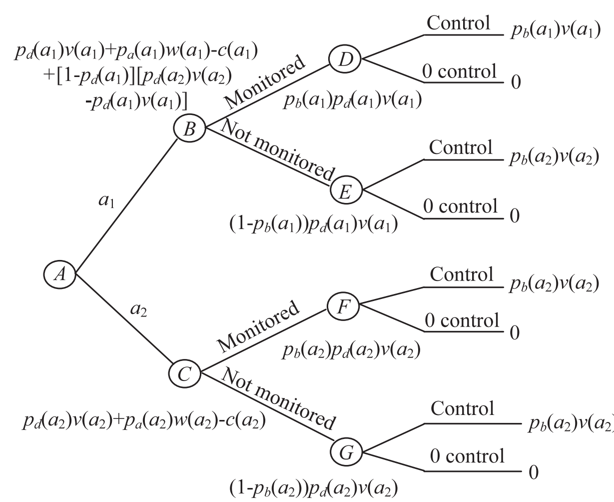

Fig. 1. Game tree of the unsafe behavior monitoring scheme.

According to the return probability described above, the coal miner game tree of unsafe behavior monitoring is shown as Fig. 1.

3. Utility analysis of the coal miner's choice

Monitoring can be considered effective if the coal miner chooses the safe behavior, a_2, consistent with the operator's intention. If the choice is unsafe behavior, a_1, the monitoring is considered a failure. This is modeled as described below.

For the coal miner, suppose $U(a_1)$ is the expected total return for choosing unsafe behavior a_1 .

$$U(a_1) = p_a(a_1)w(a_1) - c(a_1) + p_d(a_1)v(a_1) + [1 - p_b(a_1)] \times [p_d(a_2)v(a_2) - p_d(a_1)v(a_1)] \quad (1)$$

The expected total return for choosing the safe behavior, $U(a_2)$, is

$$U(a_2) = p_a(a_2)w(a_2) - c(a_2) + p_d(a_2)v(a_2) \quad (2)$$

Therefore, the condition $U(a_2) > U(a_1)$ must be satisfied if the coal miner chooses the encouraged safe behavior, a_2. That is to say,

$$p_a(a_2)w(a_2) - c(a_2) + p_d(a_2)v(a_2) > p_a(a_1)w(a_1) - c(a_1) + p_d(a_1)v(a_1) + [1 - p_b(a_1)] \times [p_d(a_2)v(a_2) - p_d(a_1)v(a_1)] \quad (3)$$

$$p_b(a_1) > \frac{p_a(a_1)w(a_1) - p_a(a_2)w(a_2) + c(a_2) - c(a_1)}{p_d(a_2)v(a_2) - p_d(a_1)v(a_1)} \quad (4)$$

The relationship among model factors will be analyzed for effective monitoring.

The term $p_b(a_1)$ is defined as the monitoring intensity. Suppose $p_d(a_2)v(a_2) - p_d(a_1)v(a_1)$ is the expected value difference of the control return and $c(a_2) - c(a_1)$ is the behavior cost difference.