Risk Analysis and Intervention Policy Research of Miners' Unsafe Behavior Based on System Dynamics

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Abstract: With the application and development of the discipline of safety science and safety economy in enterprises, people gradually began to realize that the unsafe behavior of employees themselves is an important source of coal mine safety issues. This paper constructs a behavioral risk model based on the employee behavior risk in coal mines combined with ALARP principle, and establishes a coal mine safety production organization behavior expectation utility model based on von Neumann Morgan Stan's utility function. Based on this risk model, employees at different stages are Risk attitude analysis of risk appetite, using Vensim software to construct the model of unsafe behavior level of coal mine workers, and obtaining the trend of unsafe behavior level of coal mine workers through model simulation. Based on the simulation results, the behavioral risk management decision research is carried out to realize the behavior of coal mine employees.

1. Introduction

1.1 Research Background and Current Situation
The results show that, among the main causes of coal mine accidents, people's illegal operation and irrational command account for nearly 90%. Risk-related actions often bring benefits and safety costs due to exposure. How to combine risk acceptability research with safety economic field reasonably, and realize both risk management and economic income of coal enterprises is the only way for coal enterprises to seek long-term development.

Risk research is based on the acceptability of risk. At present, the main method used to study the acceptability of risk in the world is the "ALARP" principle[3]. On the basis of risk analysis theory, Chauncey Starr puts forward a set of rational behavior paradigms, and explores the relationship between perceived benefits and willingness to take risks. Some foreign experts and scholars applied the ALARP principle in dam, pressure pipeline and other aspects through the study of risk tolerance.

Based on the experience of risk management abroad, the research on unsafe behavior and behavioral risk of employees in enterprises in China started relatively late. Zhou Gang (2008) and others put forward that human error means that the result of human behavior deviates from the prescribed goal, or exceeds the acceptable limit, resulting in adverse effects[4]. Cao Qingren (2011) wrote "The Theory and Method of Unsafe Behavior Management of Coal Mine Employees". Through
the analysis of the cognitive psychological process of coal mine employees and coal mine managers, a relatively complete theoretical system of safety management of coal mine employees is constructed, which provides theoretical reference for coal mine safety management and safety practice[5].

Reasonable risk definition is an important basis for quantitative risk assessment, and risk preference is a main method for quantitative risk assessment. In the field of economics, risk preference is mainly aimed at uncertain risk factors, and unsafe behavior has the same uncertainty. Therefore, risk preference is more and more applied in the field of safety behavior and safety economy. Deng Yulin et al. (2007) studied risk preference and risk cost, analyzed the characteristics of knowledge workers' risk preference, and studied the relationship between risk preference and incentive [6]. But generally speaking, the research on unsafe behavior of coal miners in China is less related to risk preference, and the research factors involved are relatively broad[7].

2. Construction and Analysis of Safety Input Model Based on ALARP Principle

2.1 An Analysis of the Economic Essence of ALARP Principle

From the point of view of safety investment, the key to realize coal mine safety management is to realize the management and control of coal mine workers' behavioral risk. Scientific and reasonable risk measurement of coal mine workers' behavioral risk has become the focus of coal mine safety management. This paper combines ALARP principle with risk preference method to explore the relationship between behavioral risk and safety investment.

The As Low As Reasonably Practicable principle (the lowest reasonable and feasible) is the most common risk criterion as the acceptable level of risk in foreign countries. The meaning of ALARP principle is that any industrial system is accompanied by risks, and risks cannot be completely eliminated through simple preventive and control measures. At the same time, the more optimized the risk level of any system, the more difficult it is to further reduce the risk, and the safety input cost associated with it tends to rise exponentially. It can also be said that the marginal benefit of investment in safety improvement measures decreases gradually and eventually tends to zero or even negative[8].

In the ALARP principle, the risk interval is divided into risk serious area, ALARP area (also known as tolerable area) and negligible area by intolerable line and negligible line. The key points of project risk identification and the main objects of risk control measures are mainly focused on the areas of serious risk and ALARP.

Like the production activities of the coal system, activities that take safety measures and reduce the risk of behavior of coal workers are also economic behaviors, and they also have common economic laws. The economic essence of the "ALARP Principles" is mainly reflected in:

1) If a system does not take any safety control measures against the existing risks, the system will always be in the highest risk state, that is, the risk area in the ALARP principle.

2) In the process of investment in safety measures, risk increases first and then decreases as the marginal output of factors of production. It is not a linear function relationship, that is to say, safety investment in risk management will have an optimal economic benefit point.

3) When the system risk level is reduced to a certain extent, the system risk will not be significantly reduced even if the security investment is increased. This also shows that the risk of any system can only be controlled within an appropriate range and cannot be completely eliminated.

2.2 Model establishment

In 1992, Dr. Gary S. Baker, professor of economics and sociology at the University of Chicago, considered human behavior as a result of cost-benefit analysis. Only when the expected cost is less than or equal to the expected benefit, can human motivation be translated into real behavior [9]. According to the logical calculation between cost and benefit in the system, human behavior tendency can be explained and predicted by the calculation results. Based on the characteristics of autonomy, concealment and uncertainty of unsafe behavior in coal mine safety production. Using the
investment-benefit curve proposed by Votey, an American scholar, and combining ALARP principle with risk preference, a model is constructed, as shown in Fig 1.

![Security Investment Benefit Model](image)

**Figure 1. Security Investment Benefit Model**

The basic idea of the investment-benefit curve in the model is as follows: when safety input is between 0 and B, the net income value of safety production of coal mine enterprises is negative, because in the early stage of safety input, the effect appears slowly, even negative effect. In this stage, when safety input is at point A, the net income of safety production reaches the lowest point; when safety economic input reaches point B, the net income of safety production reaches the lowest point. When the safety input is between B and D, with the increase of safety input, the coal mining enterprises begin to make profits, and the net income is positive. Point C is the turning point of marginal effect of net income from increasing to decreasing. It can be seen that the growth rate of income in BC segment is the highest, while that in CD segment is slowed down. When the safety input reaches point D, the net income of enterprises reaches the maximum.

2.3 Model analysis

In order to deeply analyze the safety investment benefit model, the risk preference method is adopted here. The concept of risk preference is based on the theory of risk tolerance. Behavior risk preference is the tendency of employees' behavior or attitude in the face of uncertain risks and hidden dangers in order to achieve their task objectives in safe production. In order to realize the quantitative calculation of behavioral risk preference, the concept of "utility" is introduced here as a form of expression to measure workers' behavior in coal mine safety production. The expected utility model of coal mine safety production organization behavior based on von Neumann Morgenstein utility function is established.

Expected utility function form:

$$\sum_{i=1}^{n} F \left( p_i \right) U \left( x_i \right)$$

In the formula: U represents the utility function of the possible result evaluation; F is the weight of objective probability; n is the number of possible results; Pi is the objective probability of the result; Xi is the possible result.

When coal miners conduct behavioral activities, $x_1$ and $x_2$ represent the two kinds of behavioral utility of safety and unsafe behaviors respectively, and the probability of occurrence is $p$ and $1-p$, respectively. Therefore, the different utility corresponding to the different income generated by the behavior activities of coal miners is $ux$. The weighted average of these utility is the expected utility of the behavior safety of coal miners. The expression is as follows:
3. Behavioral Risk Analysis and Risk Management Decision-making Research

3.1. Behavioral Risk Analysis

The unsafe behavior of coal mine workers is an economic behavior that is subject to the law of input and output in a certain sense [10]. The behavioral risk appetite of employees is mainly reflected in four aspects: safety investment, safety performance level, and safety management level and employee safety quality.

The safety quality of employees is the main factor of behavioral risk, and the behavioral risk preference explains the attitude of employees themselves when dealing with risks from the perspective of coal miners. Behavioral risk appetite is divided into psychological preference and behavioral intention preference. The risk psychological preference of coal miners is a psychological tendency of risk in terms of thinking, which is understood as a subjective thinking process for employees to treat risks. Coal miners' behavioral intention preference is the behavioral judgment that they may make on risk, and it is also the result of psychological preference, which ultimately promotes workers' unsafe behavior.

3.2. Establishment of SD-based unsafe behavior level model

Based on the principle of system dynamics and the theory of safety investment benefit, this paper quantifies the influencing factors of unsafe behavior level of coal miners, and finally constructs a decision model of unsafe behavior level, as shown in Figure 3.

All the formulas in the model are derived from the Equations formula editing function module in Vensim software. The weights of each state variable are determined by AHP, and the main simulation equation of safe behavior level is obtained:

The level of unsafe behavior = the increment of unsafe behavior level - the decrease of unsafe behavior level.

Incremental level of unsafe behavior = 0.32 * operation error + 0.27 * non-compliance + 0.18 * safety target gap + 0.11 * neglect of safety warning + 0.09 * non-compliance with requirements + 0.03 * venture into the workplace;

Unsafe Behavior Level Decrease = 0.24 * Safety Specification + 0.19 * Behavior Tracking Capture + 0.31 x Risk Handling Ability + 0.26 * Risk Cognition
3.3 Analysis of model simulation results

The initial values of each decision variable in the model and the assignment settings after the decision are shown in Table 1.

| Decision variables         | initial value | Post decision value | Upper limit value |
|----------------------------|---------------|---------------------|-------------------|
| Capital input              | 20            | 40                  | 100               |
| Maximum Safety Input       | 100           | 200                 | 1000              |
| Enterprise benefit         | 20            | 40                  | 100               |
| Safety supervision         | 20            | 40                  | 100               |
| Safety target              | 400           | 1000                | 2000              |
| Expected performance       | 1000          | 2500                | 5000              |
| Educational level          | 25            | 60                  | 200               |
| work experience            | 20            | 30                  | 100               |
| Reasonable rest time       | 25            | 40                  | 200               |

When the safety input, safety performance level, safety management level, staff safety quality and unsafe behavior level in the model are at the initial value, the curves are shown in A curve in Figure 4. By optimizing the decision-making for unsafe behavior level, the decision variables in the model are improved on the basis of the original value, and the post-decision value is shown in Table 1.

After the decision, the curve of safety investment, safety performance level, safety management level, employee safety quality, and unsafe behavior level is changed to B in Figure 4.
Figure 4. Behavioral risk decision comparison chart

It can be seen from the figure that in the first to the twelfth month, the safety input, safety performance level, safety management level, employee safety quality, and unsafe behavior level are all small changes before and after the decision-making stage. In particular, the level of unsafe behavior has changed little. Corresponding to the previous explanation, this stage is still in the risk-loving area, and the behavioral risk is serious.

From the graph, it can be seen that in the 12th to 30th month, the variables changed greatly, and the quality of safety input, safety performance and management level of employees from different walks of life has been greatly improved, and the effect is remarkable. Compared with the previous 12 months, the level of unsafe behavior has been significantly reduced, which shows that it has played an effective role in decision-making. Therefore, at this stage can be considered as a risk-neutral area, that is, the ALARPA area, employees in this stage of behavioral risk tolerance has been rapidly improved.

After 30 months, relative safety input, safety performance level, safety management level, staff safety quality and unsafe behavior level before decision-making tended to be stable, reaching the optimal state after decision-making. In response to the risk aversion stage or risk tolerant area, workers have achieved the improvement of the overall safety quality in this stage, that is, to achieve safety production, but also to ensure their own safety, bring safety benefits, but also bring more wage earnings for themselves. The optimal overall security status also represents the overall risk tolerance to maximize, at this stage, some can be found to feel the existence of smaller risks.

But on the whole, safety input and safety performance have a greater impact on the level of unsafe behavior of coal miners. The most direct reflection of the relationship between economic and behavioral risk. The relationship among safety input, safety performance and unsafe behavior level is fitted by MATLAB software, and the results are shown in Fig. 5.
4. Conclusions

(1) On the basis of benefit and investment curve, combined with ALARP principle, the behavioral risk of coal miners in different stages has been analyzed, and the risk preference of different stages is put forward according to the safety production benefit of different stages. Overall: at the initial stage of investment, the safety benefits are negative. The overall behavioral risk appetite of coal mine workers tends to be risk-sensitive, which is a serious risk area. After this stage, safety production benefits begin to appear, and the safety effect is significant. Risk appetite tends to be risk neutral and is the ALARP area;

Further, the growth rate of safety benefits slows down, and gradually reaches the most advantageous advantages of coal enterprises' safety benefits. The risk attitude of employees is risk aversion, and this stage allows the existence of some risks under the conditions of perfect safety measures, that is, risk negligible areas.

(2) To manage and control the behavior risk of coal enterprises is an important direction for the future development of enterprises. On the one hand, it can improve the safety awareness skills of employees, create a good safety culture, prevent and control the unsafe behavior of employees; on the other hand, it can also maximize the safety production benefits of coal enterprises.

References:
[1] Zhou, B., Zhu, Y.H. &Tan F.M., Analysis of Unsafe Behavior Control and Its Importance of Coal Mine Workers. Value Engineering, 2011, (2): 97-99
[2] Bai, W.Y., Zhao, Y.S., Analysis and Countermeasures of Safety Investment in Coal Mine Enterprises. Coal Mine Safety, 2005, (5): 49-51
[3] Shang, Z.Z., Liu, X.L., A Review of Foreign Acceptable Risk Standards. World Geography Research, 2010, (3): 72-80
[4] Zhou, G., Cheng, W.M.&Zhuge, F.M., Analysis and Discussion on the Principles of Human Errors and Unsafe Behaviors. Chinese Journal of Safety Science, 2008, 18(3): 10-14
[5] Cao, Q.R., Theory and Method of Unsafe Behavior Management of Coal Mine Employees. Beijing: Economic Management Press, 2011.
[6] Deng, Y.L., Wang, W.P.&Da, Q.L., Research on Incentive Mechanism for Knowledge Workers Based on Variable Risk Preferences. Management Daily. 2007, 21 (02): 29-34.
[7] Han, X.J., Study on the Impact of Risk Preference on Unsafe Behavior of Miners. Xi'an University of Science and Technology: Xi'an University of Science and Technology, 2014.
[8] Luo, H.B., Theory and Application of Quantitative Risk Assessment for Industrial Systems. Tianjin University: Tianjin University, 1999.
[9] Zhang, J.G., Research on Management Countermeasure of Miners' Violation Behavior in Coal Mines. Hebei Engineering University: Hebei Engineering University, 2013.

[10] Shui, Y.B., Tian, S.C. & Li, H., Economic Analysis of Organizational Behavior of Coal Mine Safety Production. Mining Safety and Environmental Protection, 2015, (4): 117-120.