sustainability

*Article*

# The Dynamic Evolution Law of Coal Mine Workers' Behavior Risk Based on Game Theory

**Jifeng Lu [1,2], Weihua Liu [3], Kai Yu [1,2,*] and Lujie Zhou [1]**

[1] College of Safety and Environmental Engineering, Shandong University of Science and Technology, Qingdao 266590, China; lskdjf2019@163.com (J.L.); anxintech2022@163.com (L.Z.)
[2] Min an Institute of Emergency and Safety Management of Qingdao West Coast New Area, Qingdao 266590, China
[3] State Nuclear Power Engineering Company, Shanghai 200233, China; sldwuhst@163.com
* Correspondence: ykxfkd@sdust.edu.cn; Tel.: +86-139-6984-9358

**Abstract:** In the safety production system of coal mining enterprises, the income of workers affects the evolution of group behavior and then affects risky behaviors. Due to the nonlinearity and chaos of group behavior, its evolution is long and complex. This study investigated the dynamic evolution process of coal miners' group behavior to explore the law of group safety behavior and effectively promoted the safety of group behavior. First, a questionnaire survey was conducted on the influencing factors of coal mine workers' group safety behavior. Then, based on the results of the questionnaire, the coefficients of the influencing factors were obtained, and the game model was established. Finally, the game income was simulated and analyzed. The results showed that the income of workers was positively correlated with the safety of group behavior. Safety performance could effectively improve the level of group safety behavior. The safety management system of coal mining enterprises was further improved and expanded and was applied. The statistical analysis of the violations showed that the results of this study could be used to influence the risky group behavior of coal mine workers and improve the level of coal mine safety production.

**Keywords:** human factors; risk; behavior; evolutionary game; safety



**Citation:** Lu, J.; Liu, W.; Yu, K.; Zhou, L. The Dynamic Evolution Law of Coal Mine Workers' Behavior Risk Based on Game Theory. *Sustainability* **2022**, *14*, 4015. https://doi.org/10.3390/su14074015

Academic Editors: Myrto Konstantinidou and Michalis Christou

Received: 14 February 2022
Accepted: 25 March 2022
Published: 29 March 2022



## 1. Introduction

Data show that more than 80% of coal mine accidents are directly or indirectly caused by unsafe human behavior [1]. In the safety production of coal mining enterprises, individual workers are often dependent on and influenced by the group (Figure 1) [2]. The game between groups influences the behavioral choices of group members. The symmetry of the behavioral choices of safe or unsafe groups will directly affect the safe production of coal mines. The symmetry of behavior choice determines whether the behavior chosen by employees is safe. This choice has reached a relatively stable state in the employee group, which is the symmetry of behavior choice, and this state will be affected by the benefits of group behavior choices. This study aimed to investigate the evolution law of group behavior when this symmetry is broken [3,4]. It is important to study the game process of coal miners' safety behavior and analyze its evolution law to adjust the coal miners' income and improve the level of safety behavior. Therefore, the research scope of this study was the dynamic evolution process of safety behavior among coal mine workers. The purpose was to explore the influence law of the safety benefits on the safety behavior and then guide coal mine enterprises to formulate management measures.

This study investigated the dynamic evolution process of coal mine workers' group safety behavior to analyze its evolution law; it also investigated the effect of the income of workers' individual safety behavior on group behavior using game theory, which enriches the research theory of coal mine workers' group safety behavior. The research provides a theoretical basis for the safety management decision making of coal mining enterprises.

The result was applied to coal mine enterprises and provides application methods for the control of safety behavior.

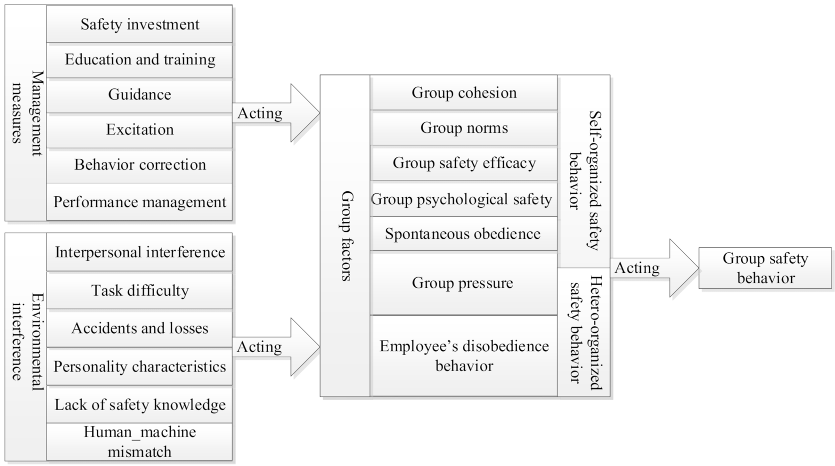



**Figure 1.** Action principle of a group on safety behavior.

The causes of accidents are various, mainly including two categories: one is people's unsafe behavior, the other is the unsafe state of things [5]. Safety behavior is a complex system engineering issue and its causes are diverse. In order to facilitate the study of safety behavior, a variety of accident models were created. The "cheese" accident model is one of the most famous models. It believes that the potential risks in the system destroy the defense at all levels and eventually lead to accidents [6]. The safety behavior of employees is affected by safety leadership and working conditions [7]. Technology, human intervention, organizational climate and leadership style have positive effects on behavior [8–10]. Leadership safety behavior is regarded as an important factor that affects enterprise safety performance [11]. In addition, qualitative simulation technology is used to comprehensively and systematically simulate the group safety behavior of coal miners, where the control strategy of coal miners' unsafe behavior was analyzed by using ANP and SD methods [12,13]. The theory of safe behavior lays a theoretical foundation for this study to investigate the dynamic evolution process of group behavior. The causes of these safety behaviors provide theoretical support and research ideas for the design of questionnaires and dynamic evolutionary game analysis.

In recent years, interest symmetry and behavior stability have attracted the attention of many experts. Corporate image and customer relationships play roles in regulating symmetry in the association between marketing and medical tools [14]. A new concept of behavioral instability was proposed to measure behavioral traits [15]. Due to game interest asymmetry between managers and coal miners, the stability of workers' behavior is affected, resulting in unsafe behavior [4].

Most studies focused on the formation mechanism and factor model of workers' safety behavior; only a few studies further focus on the dynamic evolution process and income and behavior choice symmetry, but the number of studies shows an increasing trend. This is because the ultimate goal of safety behavior research is to obtain behavior control methods and improve the level of safety production. This has led most studies to conduct in-depth research on the formation process and factor analysis of safety behavior. It is undeniable that these studies enrich the research field of safe behavior. However, in actual safety production, the working environment of workers is affected by factors such as the group and salary. Whether the income is balanced directly affects the enthusiasm of workers, and then affects the direction development of group behavior. Based on this, more and more studies have paid attention to the benefits of workers and the impact of groups. Therefore, this study used the method of dynamic evolutionary game theory to analyze the symmetry of employee behavior and the process of dynamic evolution.

Game theory has been widely used in many fields and is of great significance to economics, engineering and sociology [16]. Game theory has also been applied to the improvement of energy, resources and environment, such as coal mine safety accidents [17,18], safety management measures [19], optimal allocation of defensive resources [20], the interaction between stakeholders in safety inspection system [21,22], and energy price based on environmental protection and game theory [23]. Game theory has also been used to study the impact of worker mobility [24], tax revenue in the thermal power industry [25] and the relevant interactive relationship between government, small enterprises and employees [26].

In this study, the influencing factors of safety behavior were determined using questionnaires. Then, the safety behavior payoff matrix of the group was constructed. Based on this matrix, different game strategies were simulated and the dynamic evolutionary law and symmetry of coal mine workers' behavior were deeply analyzed.

## 2. Methods

### 2.1. Questionnaire Analysis

In order to make the simulation results more reliable, we designed a questionnaire according to the characteristics of the influencing factors of the safety behavior of coal miners [27,28]. The questionnaire was mainly carried out in three stages (literature research, actual research and pre-investigation).

(1) Literature research stage: On the basis of consulting a large number of research results on safety behavior, the formation mechanism and influencing factors of safety behavior stability were established, and the influencing factors system is preliminarily extracted. In order to quickly obtain the required influencing factors from the large literature, we extracted the required data from the literature library with the help of text recognition and mining technology, as shown in Figure 2.

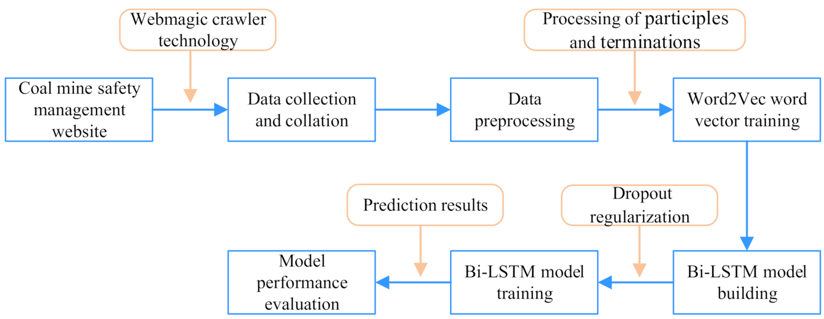



**Figure 2.** Text data mining process.

(2) Actual research stage: The influencing factors system was fed back to the experts in the research group. After consulting all members of the research group, the initial influencing factors system was adjusted. Then, several coal mines were surveyed to collect information on three violations (illegal command, illegal operation and violation of labor discipline), and technical personnel and managers in front-line production were investigated and interviewed to further adjust the influencing factors system. Subsequently, the system of influencing factors was referred to experts for final consideration. After determining the influencing factors system, the questionnaire was designed according to the specific significance of influencing factors. Finally, the final draft of the questionnaire was formed after three examinations by experts of the research group.

(3) Pre-investigation stage: In order to further verify the feasibility of the questionnaire, pre-investigation was carried out with a small sample, mainly including 2 professors, 6 lecturers, 4 doctors and 13 coal mine technicians and workers. Professors, lecturers and doctors reviewed whether the questionnaire was reasonable and feasible, and coal mine technicians and workers answered the questionnaire. By analyzing the

reliability and validity of the pre-survey results, the feasibility of the questionnaire was determined.

The questionnaire was divided into four parts: (1) instructions for filling in the survey, (2) investigation purposes and related concepts, (3) basic personal information of the respondents and (4) investigation of the safety behavior information of coal miners. In order to improve the accuracy of quantitative analysis, the Richter scale method was used to design the options of the related factors. Respondents were asked to select the options for each test item. The attribute values of the five options ranged from low to high and were scored from 1 to 5, respectively.

The relationship between the questionnaire title and the investigation factors is shown in Table 1. The numbers in Table 1 represent the questions in the questionnaire, and the factors column represents the corresponding influencing factor of that question

**Table 1.** Relationship between questions and factors of questionnaire *.

| Questions | Factors | Questions | Factors |
|---|---|---|---|
| 1 | Working years | 13 | Safety supervision |
| 2 | Education | 14 | Group pressure |
| 3 | Position | 15 | Conformity behavior |
| 4 | Safety gains | 16 | Cohesive force |
| 5 | Safety cost | 17 | Interpersonal communication |
| 6 | Psychological safety | 18 | Safety atmosphere |
| 7 | Energy-saving psychology | 19 | Group safety behavior level |
| 8 | Accident probability | 20 | Individual safety behavior level |
| 9 | Accident loss | 21 | Benefit symmetry |
| 10 | Safety performance | 22 | Behavioral stability |
| 11 | Unsafe penalties | 23 | Best time interval for behavioral intervention |
| 12 | Isolation and exclusion | 24 | Strategies for best behavior intervention |

* The questionnaire is shown in Appendix A.

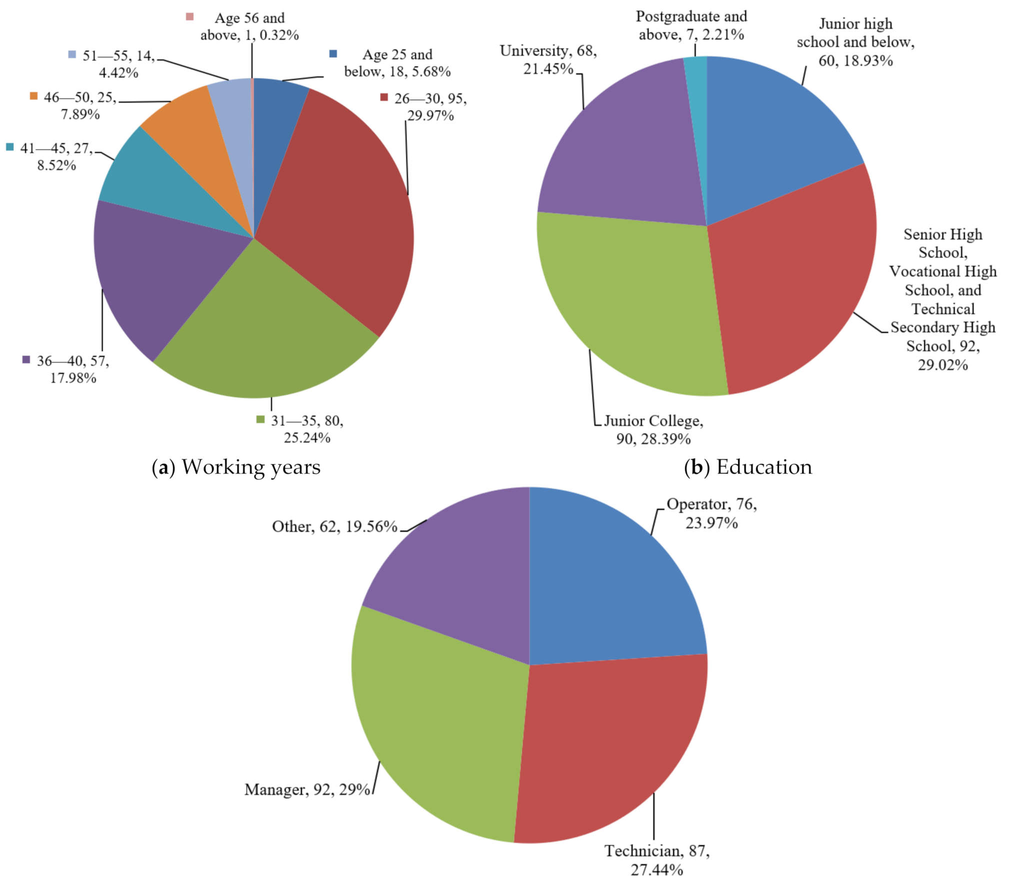
The respondents mainly included managers, technicians and front-line operators of coal mining enterprises. The questionnaires were divided into two types: paper-based questionnaires and web-based questionnaires. A total of 200 paper questionnaires were distributed and 182 were recovered, with a recovery rate was 91.00%; 146 were online questionnaires. Excluding questionnaires with missing questions and other incomplete questionnaires and invalid questionnaires that did not meet the requirements, 317 valid questionnaires were received, with an effective recovery rate of 91.62%.

Figure 3a–c gives the statistical information of the basic information of the respondents. It can be seen that the structure of the respondents in this investigation was reasonable since the respondents' working years, education and position were consistent with the reality of coal mine enterprises. It effectively ensured the reliability of the investigation results.

The reliability and validity of the results of the questionnaire needed to be analyzed [29]. The most commonly used Cronbach coefficient $\alpha$ method was used to analyze the reliability of the questionnaire (Equation (1)):

$$\alpha = (k/k-1)\left(1 - \sum_{i=1}^{k} S_i^2 / S_x^2\right) \tag{1}$$

where $k$ is the number of questions used for measurement, $S_i^2$ is the variance of the score of the $i$th question and $S_x^2$ is the variance of the total score.




(**a**) Working years (**b**) Education

(**c**) Position

**Figure 3.** (**a**) Working years, (**b**) education and (**c**) position.

The coefficient $\alpha$ evaluates the consistency of the scores of each item in the scale, which is suitable for the reliability analysis of attitude and opinion questionnaire. If $0.5 < \alpha < 0.7$, the result of the questionnaire is credible. If $0.7 < \alpha < 0.9$, the results of the questionnaire are highly credible. If $\alpha > 0.9$, the result of the questionnaire is extremely credible. The coefficient $\alpha$ was 0.841; therefore, the questionnaire was highly reliable.

The validity of the questionnaire reflected the accuracy degree of the factors investigated. In this study, the criterion correlation validity analysis was used to analyze the correlation between various factors of the questionnaire results, as shown in Equation (2):

$$R_{xx} = 1 - S_e^2 / S_x^2 \quad (2)$$

where $R_{xx}$ is the validity level and $S_e^2$ is the variance of measurement data error.

If the result is 0.01, it indicates that the possibility of interaction between factors is 99%. This shows that the questionnaire design is reasonable and the data obtained is highly reliable [30–33]. The results showed that each item reached a significance level of 0.01, which indicated that the questionnaire had a good correlation with the calibration.

The reliability and validity analysis showed that the results of the questionnaire were reliable. It was necessary to analyze the multiple linear regression coefficients of related items in the questionnaire in order to provide reliable reference factors for the establishment of the game model. SPSS 22.0 software was used to carry out a multiple linear regression analysis of the questionnaire results; the regression coefficient analysis table is shown in Table 2.

**Table 2.** Regression coefficient analysis table.

| Influence Factors | Regression Coefficient Analysis | | $t$ | $p$ |
|---|---|---|---|---|
| | Coefficient | Standard Deviation | | |
| Constant | 0.554 | 0.242 | 2.289 | 0.022 |
| Q4 | 0.691 | 0.038 | 1.828 | 0.018 |
| Q5 | 0.527 | 0.035 | 6.5 | 0 |
| Q8 | 0.409 | 0.035 | 8.942 | 0 |
| Q9 | 0.431 | 0.031 | 7.642 | 0 |
| Q10 | 0.611 | 0.021 | 7.159 | 0 |
| Q11 | 0.475 | 0.027 | 7.816 | 0 |
| Q13 | 0.677 | 0.033 | 8.497 | 0 |

Q4, Q5, Q8, Q9, Q10, Q11 and Q13 represent the order number of the questionnaire questions. For example, Q4 represents the 4th question. The questionnaire is shown in Appendix A.

### 2.2. Game Model

If the group norms tend toward safety behavior, the coal mine workers will be opposed by other coal mine workers when they choose unsafe behavior. The coal mine workers who choose unsafe behaviors are unable to easily obtain the information that the managers are checking and will be found by the managers. If the norms within the group tend toward unsafe behaviors, the group has the characteristics of sensitive communication information and strong cohesion. The group members will inform each other of the inspection whereabouts of the manager. This communication will reduce the probability of discovery by managers. However, group members' mutual notification cannot completely prevent managers from discovering their unsafe behaviors.

According to game theory and the actual characteristics of the coal mine worker group, a game hypothesis was proposed to explore the dynamic evolutionary game process between groups.

(1) The behaviors of safety managers only exist as external conditions and do not participate in the process of game selection. Safety managers all attach importance to safety, that is, they will supervise employees' behaviors and impose penalties on employees who do not attach importance to safety.
(2) Coal mine workers can get benefits r from carrying out safety behavior, such as a safety bonus. However, the cost of executing safety actions is $c$.
(3) Coal mine workers can gain benefits by choosing unsafe behaviors, such as saving energy, saving time and economic benefits. The benefit is safety cost $c$.
(4) The probability of accidents occurring when coal mine workers perform unsafe behaviors is $f$. If an accident occurs, the loss suffered by the coal mine workers is $H$.
(5) The safety managers will impose a fine on the coal mine workers after discovering that they have carried out unsafe behaviors. This will reduce the overall safety performance of the group, where the reduction amount of safety performance is expressed as $P$. In addition, they will also be isolated and excluded by workers who carry out safety behavior, which means that their psychological safety will be reduced. This is defined as an unsafe penalty, expressed as $M$.
(6) In daily work, the coal mine workers do not confirm whether the managers can conduct a safety inspection and the managers do not know whether the coal mine workers have unsafe behaviors at this time. Coal mine workers face all other workers in the group when they choose their behavior. Coal mine workers choose the same strategy and get the same income. Choosing different strategies has different benefits. The probability that unsafe behavior is discovered by a manager is $n$ ($0 < n < 1$).

A payoff matrix refers to the matrix used to describe the strategies and payments of both parties in the game [34–36]. The profits or benefits of different participants are payments. The payoff matrix for selecting different behaviors among coal mine worker groups was established, as shown in Table 3, and its process is shown in Figure 4.

**Table 3.** Payoff matrix between groups.

| | | Group 1 | |
|---|---|---|---|
| | | **Safety Behaviors** | **Unsafe Behaviors** |
| Group 2 | Safety behaviors | (0.691 * r − 0.527 * c, 0.691 * r − 0.527 * c) | (0.691 * r − 0.527 * c, 0.527 * c − 0.409 * 0.431 * f * H − 0.611 * P − 0.475 * M) |
| | Unsafe behaviors | (0.527 * c − 0.409 * 0.431 * f * H − 0.611 * P − 0.475 * M, 0.691 * r − 0.527 * c) | (0.527 * c − 0.409 * 0.431 * f * H − 0.611 * 0.677 * P * n, 0.527 * c − 0.409 * 0.431 * f * H − 0.611 * 0.677 * P * n) |

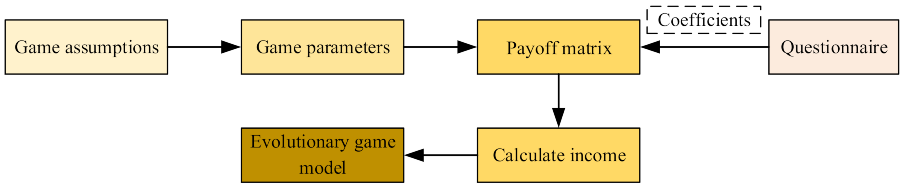



**Figure 4.** Payoff matrix process.

The probability that a coal mine worker group chooses a safety behavior is $x$, the probability of unsafe behavior is $1 - x$, and $x$ is a function of time $t$. If the average return of a strategy is higher than that of the hybrid strategy, the players will choose this strategy more. The rate of probability change of safety behavior can be expressed by using a dynamic equation.

According to the matrix, the expected return $k_1$ of safety behavior was given as

$$k_1 = x * (0.691 * r - 0.527 * c) + (1 - x) * (0.691 * r - 0.527 * c) = 0.691 * r - 0.527 * c \quad (3)$$

The expected return $k_2$ of unsafe behavior was given as

$$\begin{aligned} k_2 &= x * (0.527 * c - 0.409 * 0.431 * f * H - 0.611 * P - 0.475 * M) \\ &+ (1 - x) * (0.527 * c - 0.409 * 0.431 * f * H - 0.611 * 0.677 * P * n) \\ &= 0.527 * c - 0.409 * 0.431 * f * H - 0.611 * 0.677 * P * n \\ &- (1 - 0.677n) * 0.611 * P * x - 0.475 * M * x \end{aligned} \quad (4)$$

The average expected return $k$ of the coal mine workers group was

$$k = x * k_1 + (1 - x) * k_2 \quad (5)$$

The more rewarding a behavioral strategy is, the more it is imitated. Therefore, coal mine workers will tend to choose rewarding behaviors (safe behaviors or unsafe behaviors). The evolutionary game model used a dynamic analysis method to bring various factors affecting participants' behavior into the calculation model and systematically investigate the evolution trend of group behavior [37–39]. The evolutionary game model of the coal mine workers was as follows:

$$\begin{aligned} F(x) &= dx/dt = x * (1 - x) * (k_1 - k_2) \\ &= x * (1 - x) * [0.691 * r - 2 * 0.527 * c + 0.409 * 0.431 * f * H \\ &+ 0.611 * 0.677 * P * n + (1 - 0.677 * n) * 0.611 * P * x + 0.475 * M * x] \end{aligned} \quad (6)$$

A stability strategy in evolutionary games requires that a stable state must be robust to small disturbances. There is a linear equation of $x$ in the dynamic equation. When $x = 1$, $x = 0$ or $x^* = \frac{2*0.527*c - 0.691*r - 0.409*0.431*f*H - 0.611*0.677*P*n}{(1-0.677*n)*0.611*P + 0.475*M}$, the dynamic equation was $F(x) = 0$, which indicated that the proportion of coal mine workers that will choose safety behavior was locally stable.

Further analysis showed that the derivative of $x$ for the dynamic equation was

$$\begin{aligned} \frac{\partial F}{\partial x} &= (1 - 2x) * [0.691 * r - 2 * 0.527 * c + 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n \\ &+ (1 - 0.677 * n) * 0.611 * P * x + 0.475 * M * x] + x * (1 - x) * [(1 - 0.677 * n) * 0.611 * P + 0.475 * M] \end{aligned} \quad (7)$$

When the benefit of choosing unsafe behavior was less than that of choosing safe behavior ($0.527 * c - 0.409 * 0.431 * f * H - 0.611 * 0.677 * P * n < 0.691 * r - 0.527 * c$), there was always $F(x) \geq 0$. When x* < 0, we only consider the sign of $\frac{\partial F}{\partial x}$ when $x$ = 0 and $x$ = 1.

When $x = 1$, $\frac{\partial F}{\partial x} = 2 * 0.527 * c - 0.691 * r - 0.409 * 0.431 * f * H - 0.475 * M - 0.611 * P < 0$; $x$ = 1 is stable point.

When $x = 0$, $\frac{\partial F}{\partial x} = 0.691 * r - 2 * 0.527 * c + 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n > 0$; it can be seen that this is unstable at $x$ = 0.

Therefore, when $0.527 * c - 0.409 * 0.431 * f * H - 0.611 * 0.677 * P * n < 0.691 * r - 0.527 * c$, there is a globally unique stable point $x$ = 1. This means that when the returns of workers' safety behaviors are greater than the returns of their unsafe behaviors, the group will transform to performing safety behaviors.

When 0 < $x$* < 1, $0.611 * 0.677 * P * n < 2 * 0.527 * c - 0.691 * r - 0.409 * 0.431 * f * H < 0.611 * P + 0.475 * M$. At this time, when group 1 chooses safety behavior, the returns of group 2 choosing safety behavior are greater than that of choosing unsafe behavior. When group 1 chooses unsafe behavior, group 2 gains more from safety behavior than from unsafe behavior ($M$ < 0). In the above case, only the sign of $\frac{\partial F}{\partial x}$ is considered when $x$ = 0, $x$ = $x$* and $x$ = 1 are used.

When $x = 0$, $\frac{\partial F}{\partial x} = 0.691 * r - 2 * 0.527 * c + 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n < 0$; $x$ = 0 is stable point.

When $x$ = 1, $\frac{\partial F}{\partial x} = 2 * 0.527 * c - 0.691 * r - 0.409 * 0.431 * f * H + 0.611 * P < 0$; $x$ = 1 is stable point.

When $x$ = $x$*, $\frac{\partial F}{\partial x} = [(1 - 0.677 * n) * 0.611 * P + 0.475 * M] * x^* * (1 - x) > 0$; it can be seen that it is unstable. This means that the system will move to $x$ = 0 or $x$ = 1 due to a small interference.

It can be seen from the above that when $0.611 * 0.677 * P * n < 2 * 0.527 * c - 0.691 * r - 0.409 * 0.431 * f * H < 0.611 * P + 0.475 * M$, the dynamic equation $F$(x) has two stable points: $x$ = 0 and $x$ = 1. It can be concluded that there are two extreme points in the dynamic equation $F(x)$, which are

$$x_1 = \frac{0.691 * r - 0.611 * P + 0.409 * 0.431 * f * H + 2 * 0.611 * 0.677 * P * n - 2 * 0.527 * c - R}{2 * 0.677 * n + 0.611 * 0.677 * P * n - 2 - 0.611 * P} \tag{8}$$

$$x_2 = \frac{0.691 * r - 0.611 * P + 0.409 * 0.431 * f * H + 2 * 0.611 * 0.677 * P * n + 2 * 0.527 * c + R}{2 * 0.677 * n + 0.611 * 0.677 * P * n - 2 - 0.611 * P} \tag{9}$$

where $\begin{array}{l} R^2 = (2 * 0.611 * P - 2 * 0.691 * r - 2 * 0.409 * 0.431 f * H + 4 * 0.527 * c - 4 * 0.611 * 0.677 * P * n)^2 \\ -4(2 * 0.677 * n + 0.611 * 0.677 * P * n - 2 - 0.611 * P)(0.691 * r - 2 * 0.527 * c + 0.409 * 0.431 * f * H \\ +0.611 * 0.677 * P * n) \end{array}$.

When the probability of the group choosing safe behavior is $x \leq x_1$, the returns of the coal mine workers' group choosing safety behavior is less than that of choosing unsafe behavior, and group behavior will change to $x$ = 0; that is to say, they will choose unsafe behavior. When the probability of choosing safety behavior is $x \geq x_2$, the returns of the coal mine workers' group choosing safety behavior is greater than that of choosing unsafe behavior, and the group behavior will transform to $x$ = 1; that is to say, they will choose safety behavior. When the group chooses safety behavior with a probability of $x \in (x_1, x_2)$, the group behavior will change to $x$ = 0 or $x$ = 1. When $x$ > $x$*, group members will change to safety behavior. When $x$ < $x$*, group members will change to unsafe behavior. The dynamic of coal mine workers' group selection safety behavior is shown in Figure 5.

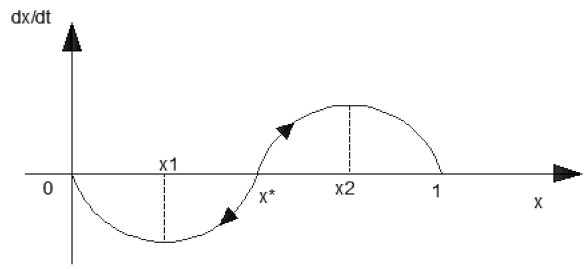



**Figure 5.** Dynamics of safety behavior selection of the coal mine workers' group.

When $0.527 * c - 0.409 * 0.431 * f * H - 0.611 * P < 0.527 * c - 0.691 * r$, this means $x^*$ = 1; that is, $(1 - 0.677 * n) * 0.611 * P * x$ takes the maximum value and there is still $F$(x) < 0. Therefore, the dynamic equation has two equilibrium points, that is, $x$ = 0 or $x$ = 1. When $x$ = 1, $\frac{\partial F}{\partial x} = 2 * 0.527 * c - 0.691 * r - 0.409 * 0.431 * f * H - 0.611 * P < 0$; this point is unstable. When $x$ = 0, $\frac{\partial F}{\partial x} = 0.691 * r - 2 * 0.527 * c + 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n < 0$; this point is stable.

Therefore, when $0.527 * c - 0.409 * 0.431 * f * H - 0.611 * P < 0.527 * c - 0.691 * r$, that is to say, the returns from the group choosing safety behavior is less than that of choosing unsafe behavior, the group behavior evolves to unsafe behavior.

## 3. Results

Here, the evolution trend of players is discussed for different strategies. The range of parameters in the simulation is as follows: $r \in [0, 2]$, $c \in [0, 2]$, $f \in [0, 1]$, $H \in [0, 2]$, $P \in [0, 2]$, $M \in [0, 2]$ and $n \in [0, 1]$. The middle value of its variation range was taken as the initial value, that is, the initial values of the seven parameters were 1, 1, 0.5, 1, 1, 1 and 0.5, respectively. The initial values of $x$ were 0.3 and 0.8.

This study focused on the dynamic evolutionary game process of group behavior under different benefits. The analysis focused on the factors closely related to workers' income, such as salary equality. Safety performance, the cost of taking safety actions (safety cost) and the loss will directly affect the income of workers. The quantitative data of the above factors mainly comes from the daily safety supervision of managers. Therefore, this study examined the returns of group safety behavior from the aspects of safety performance, safety cost, safety loss and safety supervision strength (i.e., probability of workers being inspected).

(1) The influence of safety performance on the level of group safety behavior.

When $2 * 0.527 * c - 0.691 * r < 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n$, Equation (10) was used to examine the impact of safety performance on the level of group safety behavior.

$$\frac{\partial x^*}{\partial P} = \frac{0.677 * n * (2 * 0.527 * c - 0.691 * r - 0.409 * 0.431 * f * H - 0.611 * P)}{[(1 - 0.677 * n) * 0.611 * P + 0.475 * M]^2} < 0 \quad (10)$$

This shows that increasing the punishment and reducing the safety performance will move the balance point to the left, which means that the probability of choosing safety behavior increases. The simulation results are shown in Figure 6.

Increasing the punishment from managers for unsafe behaviors meant that the impact of punishment on safety performance increased. In this case, the stable state of group behavior was broken, and the group could only maintain the returns by choosing safe behavior. When $x$ = 0.8, the convergence rate of the group behavior level was faster than that of $x$ = 0.3.

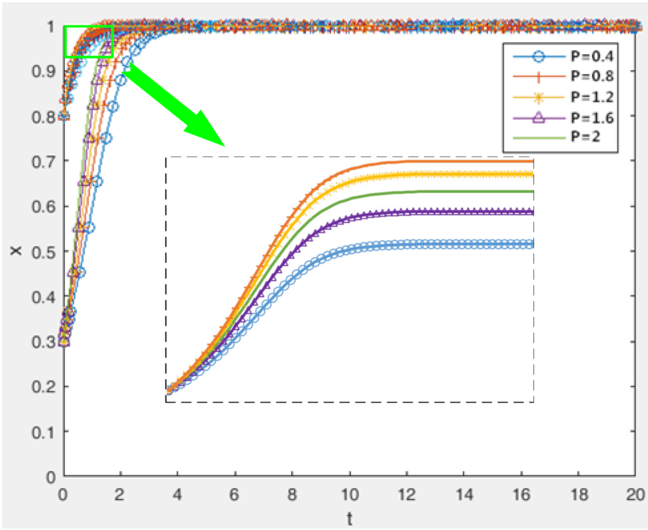



**Figure 6.** Effect of different reductions in safety performance on group behavior evolution.

(2) The influence of safety cost on the level of group safety behavior.

At $2 * 0.527 * c - 0.691 * r < 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n$, $x^*$ was derived with respect to $c$ to obtain

$$\frac{\partial x^*}{\partial c} = \frac{2}{(1 - 0.677 * n) * 0.611 * P} > 0 \quad (11)$$

An increase in the cost of performing safety behavior (i.e., an increase in the returns of choosing an unsafe behavior) moved the balance to the right. This meant that the returns of the group from choosing safety behavior were less than that of choosing unsafe behavior. Therefore, the probability of choosing safety behavior was reduced.

The impact of the safety behavior cost c on the evolution of group safety behavior is shown in Figure 7.

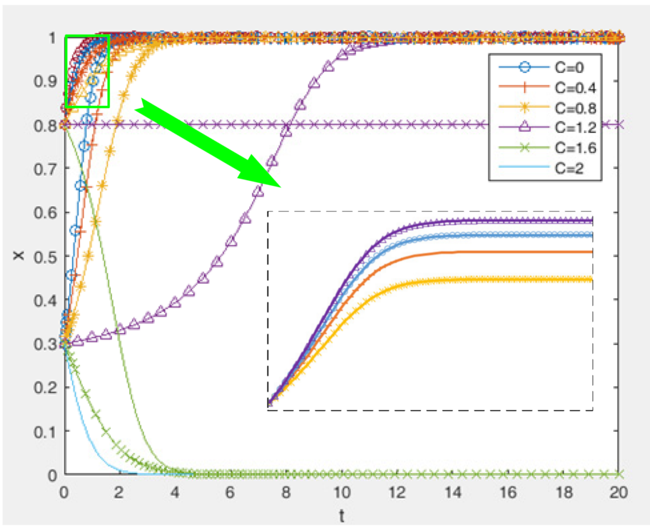



**Figure 7.** The influence of different safety behavior costs on the evolution of group behavior.

It can be seen from Figure 4 that when the level of group safety behavior was fixed, there was a threshold value for the cost of group safety behavior ($c$). When the cost of safety behavior was lower than this threshold, the group behavior evolved to safety behavior. In contrast, the behavior evolved into unsafe behavior. When equal to this threshold, the level of safety behavior did not change. When the initial value of $x$ was 0.3, the threshold value of $c$ was about 1.3. When the initial value of $x$ was 0.8, the threshold value of $c$ was 1.6. The higher the initial level of safety behavior, the higher the acceptable cost of safety behavior. The simulation results showed that if the cost of safety behavior was reduced, the safety behavior of the group evolved in the safety direction.

(3) The influence of accident loss on the level of group safety behavior.

When $2 * 0.527 * c - 0.691 * r < 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n$, $x^*$ was derived with respect to $H$ to obtain

$$\frac{\partial x^*}{\partial H} = \frac{-f}{(1 - 0.677 * n) * 0.611 * P} < 0 \quad (12)$$

The loss of unsafe behavior will break the stable state of group behavior and make the balance point move to the left. In this case, groups tend to choose safety behaviors to avoid risks and reduce losses. Therefore, the probability of the group choosing safety behavior increases.

It can be seen from Figure 8 that the probability convergence rate of group selection safety behavior increased with the increase of loss borne by the group. The convergence rate of group behavior level at $x = 0.8$ was greater than the convergence rate of group behavior level at $x = 0.3$. This shows that the higher the initial level of group safety behavior was, the faster the rate of group safety behavior level was.

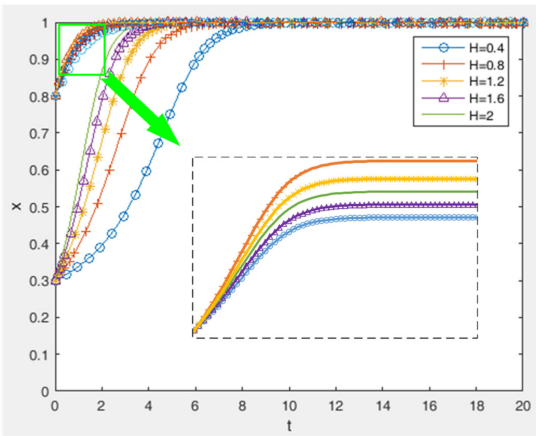



**Figure 8.** The impact of loss on group behavior.

(4) The influence of the probability of being found at the level of group safety behavior.

When $2 * 0.527 * c - 0.691 * r < 0.409 * 0.431 * f * H + 0.611 * 0.677 * P * n$, $x^*$ was derived with respect to $n$ to obtain

$$\frac{\partial x^*}{\partial n} = \frac{0.611 * P * (2 * 0.527 * c - 0.691 * r - 0.409 * 0.431 * f * H - 0.611 * P)}{[(1 - 0.677 * n) * 0.611 * P]^2} < 0 \quad (13)$$

The increase in the probability that unsafe behaviors are found by managers will move the balance point to the left. This means that if the manager strengthens the safety inspection, the probability of unsafe behaviors being found increases. As a result, the probability of the group choosing safety behavior increases. The simulation results are shown in Figure 9.

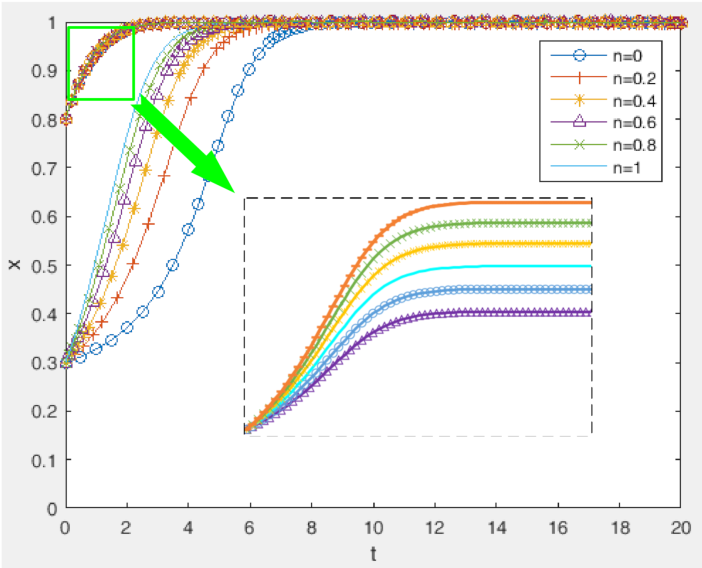



**Figure 9.** The impact of the probability of being discovered on group behavior.

The probability of unsafe behavior of group selection was increased, which changed the group returns. The group chose safety behavior to maintain the existing returns. The time required to reach a safe state was shorter. The higher the initial level of group safety behavior was, the faster the rate of group safety behavior level was.

Group self-organization behavior is a kind of spontaneous endogenous group force. Without the intervention of external concentrated forces, the change in the group's strategy only came from the interaction of group members. In coal mine production activities, group leaders should give enough information guidance and take appropriate measures to ensure that the group behavior evolves to comply with the safety code of conduct.

The above game analysis and simulation provide guidance for coal mine enterprises to guide the evolution of group safety behavior. Enterprises should strengthen safety inspections, increase punishment for unsafe behaviors, improve the proportion of safety behaviors in safety performance, increase the loss of unsafe behaviors and reduce the cost of safety behaviors. These will help to ensure the evolution of group behavior toward safety.

## 4. Discussion

Based on game analysis and calculations, the evolution law of group safety behavior is summarized here. It provides guidance for the management of coal mine workers' group safety behavior. The study took a coal mine as the research object and improved its existing rules and regulations from the aspects of safety performance, safety cost, accident loss and safety inspection. The improved rules and regulations were applied in roadway repair team 1, along with roadway repair team 2, which had a similar situation to the reference object. In January 2020, after the roadway repair team 1 strengthened the management of safety performance, reduced the safety cost, increased the accident loss and increased safety inspections, the number of "three violations" (illegal command, illegal operation and violation of labor discipline) was significantly reduced. The number of "three violations" of roadway repair team 1 and roadway repair team 2 from 2020 to 2021 (Figure 10) was observed to analyze the application effect of the research results from the study.

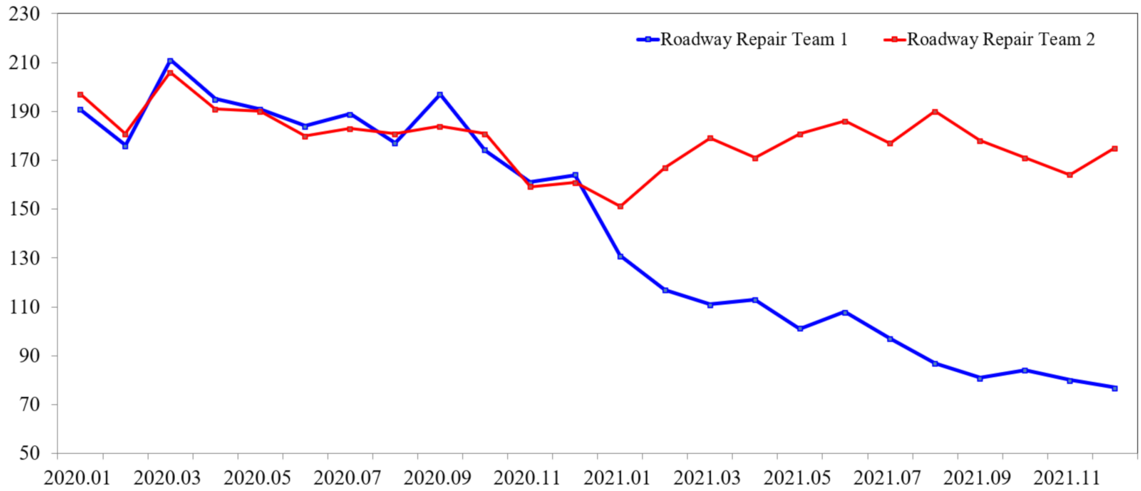



**Figure 10.** Statistics of "three violations" by the roadway repair teams 1 and 2 in 2020–2021.

It can be seen from Figure 10 that from January 2021, the number of "three violations" of roadway repair team 1 (blue curve) decreased significantly. Although there were also small fluctuations in the later period, it is still in a downward trend overall. The number of "three violations" dropped to about 80 in December 2021. It was found that the number of "three violations" of roadway repair team 2 without optimization of the relevant rules and regulations was still between 150–200 (red curve). In order to further analyze the application effect, the study compared the number of "three violations" of roadway repair team 1 in 2021 with that of roadway repair team 1 in 2020 and roadway repair team 2 in 2021 (Figure 11).

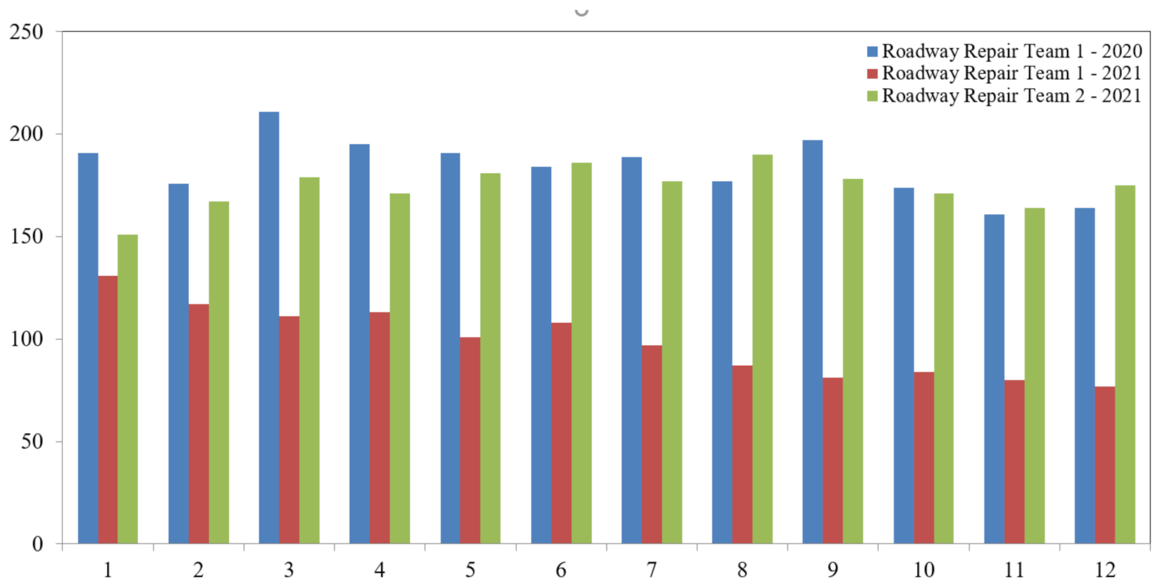



**Figure 11.** Comparison of the "three violations" between roadway repair teams 1 and 2.

It can be seen from Figure 11 that after the implementation of the new rules and regulations, the number of "three violations" per month of roadway repair team 1 in 2021 decreased significantly compared with the same period in 2020. Similarly, the number of "three violations" per month of roadway repair team 1 decreased significantly compared with that of roadway repair team 2 in 2021.

Figures 10 and 11 show that the behavior selection of coal mine workers was adjusted by improving the rules and regulations of coal enterprises. In addition, it was found that although the number of "three violations" by roadway repair team 1 in 2021 showed a downward trend, it was still around 80 at the end of the study period. This shows that the number of "three offenses" in roadway repair team 1 still had room to decline. The future research focus is to further improve their safety behavior level.

## 5. Conclusions

Based on the method of evolutionary game theory, the study took coal mine workers' groups as the research object and simulated and analyzed the dynamic game process of safety behavior between groups. The main conclusions were as follows:

(1) A questionnaire was used to analyze the influence of factors on the group behavior of coal mine workers' groups and the linear regression coefficient of factors was calculated.
(2) Combined with the statistical results of the questionnaire and the characteristics of coal mine workers, the payoff matrix was constructed and the dynamic equations were derived. The game of coal mine workers' group safety behavior was simulated. The influence and development law of the coal mine workers' group behavior selection were analyzed in terms of safety performance, safety cost, accident loss and checked probability. It was found that improving safety performance, reducing safety cost, increasing accident loss or punishment and increasing the safety inspection frequency can effectively regulate the group behavior of coal mine workers and improve the safety of group behavior.
(3) The research results were applied to a coal mine. The number of "three violations" in roadway repair team 1 and roadway repair team 2 was analyzed to verify the practical application effect of the research results.

In the process of coal mine safety production, establishing a reasonable reward and punishment mechanism can improve the income of workers' choice of safety behavior and standardize employees' safety behavior. Further, the safety behavior level of the coal mine workers group was effectively improved. The research of this study provides a theoretical basis and application reference for similar research.

**Author Contributions:** Conceptualization, K.Y.; methodology, L.Z.; validation, J.L.; formal analysis, W.L.; investigation, J.L.; resources, W.L.; data curation, K.Y.; writing—original draft preparation, K.Y.; writing—review and editing, L.Z.; supervision, J.L.; project administration, K.Y.; funding acquisition, K.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Shandong Provincial Natural Science Foundation, China, grant number ZR2020QE137, and the National Natural Science Foundation of China, grant number 51474138.

**Institutional Review Board Statement:** The study was conducted according to the guidelines of the Declaration of Helsinki, and the study was approved by the Ethics Committee of Shandong University of science and technology ([2022] 003 and date of 6 January 2021).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Acknowledgments:** The authors are thankful for the support of all coal miners, teachers and students of safety engineering and the authors of references.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Questionnaire on the safety behavior of coal mine workers**

**Part I: Basic information**

1. Number of years you have been working in the company__________________
① ≤5, ② 6—10, ③ 11—15, ④ 16—20, ⑤ >20
2. Your education is ______________________
① University, ② Junior college, ③ Senior high school, ④ Junior high school and below, ⑤ Postgraduate and above
3. Your position is ___________________________
① Operator, ② Technician, ③ Manager, ④ Other

**Part II: Safety behavior information investigation**

4. Do you think a good incentive system can improve your safety behavior at work?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
5. In order to ensure safety in production, do you pay a high safety cost?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
6. If your team (district team) has a higher level of safety during production, when carrying out high-risk operations, do you think you are safe?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
7. If in the daily production, there is a fluke, energy-saving or other psychological effect, do you think it will affect your safety in production?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
8. Has there been an accident in your work unit?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
9. After the accident, did you adjust your safety operations to reduce the accident loss?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
10. What do you think of the safety standard of your team (district team) and its safety performance?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
11. Do you think the fine has an impact on the regulation of safety behavior?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
12. Do you think that being a maverick has an impact on the safety of production operations?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
13. During work, if the supervisor gives you a timely reminder, do you think to change your bad behavior habits?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
14. Do you think group cohesion has an effect on group pressure?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
15. If you think or act differently from other colleagues, will group pressure influence you to "go with the flow" and choose the same safety behavior as other colleagues?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
16. Do you think the degree of harmony between colleagues affects the cohesion of the team (district team)?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
17. Do you think communication and mediation can help to eliminate conflicts between colleagues?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
18. Do you think a good team (district team) safety culture atmosphere leads to good team safety behavior?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
19. What do you think the overall safety behavior level of your team (district team) is?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
20. What do you think about the influence of personal safety in production on enterprise safety in production?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
21. Do you think the benefits are relatively stable and symmetrical for the team (district team) safety behavior?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
22. If your production operation habits are not good, do you think it will cause an accident?
A: None, B: Smaller, C: Average, D: Larger, E: Sure
23. In what period do you think you are most likely to break the law? (optional)
A: 8:00 A.M.–12:00 A.M., B: 12:00 A.M.–4:00 P.M., C: 4:00 P.M.–8:00 P.M.,
D: 8:00 P.M.–00:00 A.M., E: 00:00 A.M.–4:00 A.M., F: 4:00 A.M.–8:00 A.M.
24. In order to prevent or reduce your violations in the daily production process, which of the following measures do you think is the most direct and effective? (optional)
A: Safety education and training in the mine, B: Department of Safety,
C: District team management, D: Management of the team,
E: Improvement of the working environment, F: Adjustment of individual workers

## References


1. CAWS. China Administration of Work Safety. 2017. Available online: http://www.chinasafety.gov.cn/newpage/ (accessed on 19 February 2021).
2. Cao, Q.; Yu, K.; Zhou, L.; Wang, L.; Li, C. In-depth research on qualitative simulation of coal miners' group safety behaviors. *Saf. Sci.* **2019**, *113*, 210–232. [CrossRef]
3. Kirin, S.; Sedmak, A.; Li, W.; Brzakovic, M.; Miljanovic, I.; Petrovic, A.; Sedmak, S. Human factor risk management procedures applied in the case of open pit mine. *Eng. Fail. Anal.* **2021**, *126*, 105456. [CrossRef]
4. Yu, K.; Zhou, L.; Cao, Q.; Li, Z. Evolutionary Game Research on Symmetry of Workers' Behavior in Coal Mine Enterprises. *Symmetry* **2019**, *11*, 156. [CrossRef]
5. Heinrich, H.W. *Industrial Accident Prevention*; McGraw-Hill: New York, NY, USA, 1995; pp. 19–26.
6. Reason, J. A systems approach to organizational error. *Ergonomics* **1995**, *8*, 1708–1721. [CrossRef]

7. Beatriz, F.M.; José, M.M.P.; Camilo, J.V.O. The role of safety leadership and working conditions in safety performance in process industries. *J. Loss Prev. Process Ind.* **2017**, *50*, 403–415.
8. Mohammad, M.Z.; Bonaventura, H.W.H. Structural equation model of integrated safety intervention practices affecting the safety behaviour of workers in the construction industry. *Saf. Sci.* **2017**, *98*, 124–135.
9. Tristan, W.C.; Autumn, D.K. The role of effective error management practices in increasing miners' safety performance. *Saf. Sci.* **2013**, *60*, 131–141.
10. Todd, D.S.; Franklin, E.; David, M.D. Safety-specific transformational and passive leadership influences on firefighter safety climate perceptions and safety behavior outcomes. *Saf. Sci.* **2016**, *86*, 92–97.
11. Zhang, S.; Shi, X.; Wu, C. Measuring the effects of external factor on leadership safety behavior: Case study of mine enterprises in China. *Saf. Sci.* **2017**, *93*, 241–255. [CrossRef]
12. Yu, K.; Cao, Q.; Zhou, L. Study on qualitative simulation technology of group safety behaviors and the related software platform. *Comput. Ind. Eng.* **2019**, *127*, 1037–1055. [CrossRef]
13. Yu, K.; Cao, Q.; Xie, C.; Qu, N.; Zhou, L. Analysis of intervention strategies for coal miners' unsafe behaviors based onanalytic network process and system dynamics. *Saf. Sci.* **2019**, *118*, 145–157. [CrossRef]
14. Ahmed, R.R.; Channar, Z.A.; Soomro, R.H.; Vveinhardt, J.; Streimikiene, D.; Parmar, V. Antecedents of Symmetry in Physicians' Prescription Behavior: Evidence from SEM-Based Multivariate Approach. *Symmetry* **2018**, *10*, 721. [CrossRef]
15. Pertoldi, C.; Bahrndorff, S.; Novicic, Z.K.; Rohde, P.D. The Novel Concept of "Behavioural Instability" and Its Potential Applications. *Symmetry* **2016**, *8*, 135. [CrossRef]
16. Newton, J. Evolutionary Game Theory: A Renaissance. *Games* **2018**, *9*, 31. [CrossRef]
17. Jiang, T. Multi-party Game Analysis of Coal Industry and Industry Regulation Policy Optimization. In Proceedings of the 3rd International Conference on Environmental Science and Material Application (ESMA), Chongqing, China, 25–26 November 2017.
18. Zhao, R.; Neighbour, G.; Han, J. Using game theory to describe strategy selection for environmental risk and carbon emissions reduction in the green supply chain. *J. Loss Prev. Process Ind.* **2012**, *25*, 927–936. [CrossRef]
19. Zhai, X. The Management to Strengthen the Coal Mine Safety in China Based on Cooperative Game Theory. In Proceedings of the International Conference on Sports, Arts, Education and Management Engineering (SAEME), Shenyang, China, 15–16 July 2017.
20. Feng, Q.; Cai, H.; Chen, Z. Using game theory to optimize allocation of defensive resources to protect multiple chemical facilities in a city against terrorist attacks. *J. Loss Prev. Process Ind.* **2016**, *43*, 614–628. [CrossRef]
21. Liu, Q.; Li, X.; Hassall, M. Evolutionary game analysis and stability control scenarios of coal mine safety inspection system in China based on system dynamics. *Saf. Sci.* **2015**, *80*, 13–22. [CrossRef]
22. Lu, R.; Wang, X.; Yu, H. Multiparty Evolutionary Game Model in Coal Mine Safety Management and Its Application. *Complexity* **2018**, *2018*, 9620142. [CrossRef]
23. Duan, W.; Li, C.; Gong, F.; Xu, D. Ecological Study of Effect of Coal or Crude Oil Price Fluctuations on Modern Coal Chemical Projects in China. *Ekoloji* **2018**, *27*, 1879–1886.
24. Sun, J.; Wang, X.; Shen, L. Research on the mobility behaviour of Chinese construction workers based on evolutionary game theory. *Econ. Res.-Ekon. Istraz.* **2018**, *31*, 1848–1966.
25. Liu, H.; Chen, Z.; Wang, J.; Fan, J. The impact of resource tax reform on China's coal industry. *Energy Econ.* **2017**, *61*, 52–61. [CrossRef]
26. Wang, Q.; Mei, Q.; Liu, S. Analysis of Managing Safety in Small Enterprises: Dual-Effects of Employee Prosocial Safety Behavior and Government Inspection. *BioMed Res. Int.* **2018**, *2018*, 6482507. [CrossRef] [PubMed]
27. Stephen, P.R. *Organizational Behavior [Imprint]*; Pearson Education, Limited: Upper Saddle River, NJ, USA, 2010; pp. 17–32.
28. Hu, B. *The Principle and Application of Qualitative Simulation of Group Behavior*; Huazhong University of Science and Technology Press: Wuhan, China, 2006; pp. 27–39.
29. Xu, W. *SPSS Statistical Analysis Method and Its Application*; Publishing House of Electronics Industry: Beijing, China, 2017.
30. Ore, V.; Nasic, S.; Riad, J. Lower extremity range of motion and alignment: A reliability and concurrent validity study of goniometric and three-dimensional motion analysis measurement. *Heliyon* **2020**, *6*, e04713. [CrossRef] [PubMed]
31. Kang, H.-K. Examination of the Validity of Adolescent Leisure Lifestyle Questionnaire. *Korean J. Converg. Sci.* **2021**, *10*, 107–121.
32. Anderson, R.; Taylor, S.; Taylor, T.; Virues-Ortega, J. Thematic and textual analysis methods for developing social validity questionnaires in applied behavior analysis. *Behav. Interv.* **2021**, *1832*, 1–22. [CrossRef]
33. Piemontese, L.; Neudert, R.; Oberlack, C.; Pedde, S.; Roggero, M.; Buchadas, A.; Martin, D.A.; Orozco, R.; Pellowe, K.; Segnon, A.C. Validity and validation in archetype analysis: Practical assessment framework and guidelines. *Environ. Res. Lett.* **2022**, *17*, 025010. [CrossRef]
34. Xia, M.M. Methods for solving matrix games with cross-evaluated payoffs. *Soft Comput.* **2019**, *23*, 11123–11140. [CrossRef]
35. Verma, T. A novel method for solving constrained matrix games with fuzzy payoffs. *J. Intell. Fuzzy Syst.* **2021**, *40*, 191–204. [CrossRef]
36. Verma, R.; Aggarwal, A. On matrix games with 2-tuple intuitionistic fuzzy linguistic payoffs. *Iran. J. Fuzzy Syst.* **2021**, *18*, 149–167.
37. Migot, T.; Cojocaru, M.G. On Minty-variational inequalities and evolutionary stable states of generalized monotone games. *Oper. Res. Lett.* **2021**, *49*, 96–100. [CrossRef]
38. Narang, A.; Shaiju, A.J. Stability of faces in asymmetric evolutionary games. *Ann. Oper. Res.* **2021**, *304*, 343–359. [CrossRef]
39. McGlothlin, J.W.; Akcay, E.; Brodie, E.D.; Moore, A.J.; Van Cleve, J. A Synthesis of Game Theory and Quantitative Genetic Models of Social Evolution. *J. Hered.* **2022**, *113*, 109–119. [CrossRef] [PubMed]