Evolution dynamic of intelligent construction strategy of coal mine enterprises in China

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A B S T R A C T

The intelligent construction of coal mining enterprises is the fundamental strategy to prevent and curb major coal mine accidents, and the core technical support to realize the high-quality development of the coal industry. Considering the intelligent construction of coal mining enterprises enabled by emerging information technologies such as 5G and artificial intelligence, this paper constructs a Moran process stochastic evolutionary game model of intelligent construction of coal mining enterprises. Based on the fixed point probability of the Moran process, the probability of successful invasion of the "intelligent construction" strategy and the "traditional production" strategy in the limited coal mining enterprise group is calculated. By comparing the probability of individual fixed point and the probability of neutral mutation, the dominant condition of the strategy under strong selection and weak selection is obtained. The research shows that external stochastic factors, the number and scale of enterprises, the intensity of capacity replacement and the cost-benefit of intelligent construction are the main factors affecting the intelligent construction behavior of coal mining enterprises. When the intelligent construction of coal mining enterprises is in the cultivation period, the intelligent construction of underground coal mines dominated by stochastic factors can be effectively promoted by increasing the intensity of capacity reduction replacement. For the open-pit coal mine dominated by expected payoffs, reducing the number of mining rights and improving the concentration of open-pit coal mining industry will have a better effect on promoting its intelligent cultivation process. When the intelligent construction of coal mining enterprises is in the mature stage, with the improvement of the cost and benefits of intelligent construction, "intelligent construction" strategy will become a general consensus of coal mining enterprises. In addition, this paper analyzes the relevant parameters through specific examples to verify the effectiveness of the conclusions, which provides a scientific basis for effectively accelerating the intelligent construction of coal mining enterprises and promoting the transformation and upgrading of the coal industry.

1. Introduction

Coal is the most economical and reliable resource in primary energy. The development stage of China’s industrialization and the characteristics of energy resources endowments determine that coal will still be the main energy to support China’s economic development for a long time in the future. There are about 5,000 existing coal mines in China, of which more than 90% are underground coal mines. Traditional coal mining is dominated by manual labor. Different from the working environment of general occupation, the underground mining environment of coal mine is extremely harsh, with high temperature, high pressure, high gas and other risk characteristics. The harsh underground working environment seriously threatens the safety of miners. In order to reduce the impact of similar disasters on miners, existing research has mainly increased the safety performance of mining operations by improving the operating environment (Lewis-Beck and Alford, 1980; Tripathy and Ala, 2018), optimizing the management mode (Paul and Maiti, 2007; Foster and Hoult, 2013), and improving the reliability of operating equipment (Furuly et al., 2013; Ahmadi et al., 2019). Although some achievements have been made, coal mine safety accidents still occur from time to time.
in China, and coal mine safety performance is in a state of fluctuation (Yang et al., 2020; Liu et al., 2019). China has become the country with the largest death toll in the coal mine industry (Liu et al., 2015; Liu et al., 2017). There are two main reasons for the above phenomenon. a. Coal mining under the condition of insufficient technical support has the characteristics of geological environment risk. For coal mining enterprises, restricted by the level of intelligent technology, it is difficult for coal mining enterprises to accurately explore the geological environment, and the changeable geological environment potentially threatens the life safety of miners; b. The coal mining process with the participation of miners has the characteristics of individual behavior risk. For miners, unsafe behavior of miners is the main cause of coal mine safety accidents (Wang et al., 2019; Tong et al., 2019; Qiao et al., 2018). Individuals have the characteristics of bounded rationality. Under the interference of complex geological environment and negative emotions, unsafe behaviors are always accompanied by individuals. Based on this, improving the intelligent level of mining equipment and realizing unmanned mining can effectively eliminate the geological environment risk and individual behavior risk, which has become an important way for the high-quality development of China's coal industry. In recent years, emerging technologies such as 5G and artificial intelligence have provided technical support for coal mining enterprises to realize intelligent unmanned mining (Abiodun et al., 2018), such as coal mine transparent geological information system based on Internet of Things, big data and other information technologies, coal mine intelligent robot underground operation, etc. In 2020, Multiple departments of the Chinese Government jointly issued the Guiding Opinions on Accelerating the Intelligent Development of Coal Mines. It is pointed out that the integrated development of intelligent technology and coal industry should be accelerated to improve the intelligent level of coal mine. The intelligent construction of coal mine has become an effective way to promote the transformation and upgrading of coal industry. Referring to the existing research (Zhang et al., 2022), the intelligent construction of coal mine refers to the process of forming an intelligent production system with independent decision-making and execution by using 5G, artificial intelligence and other advanced technologies to achieve unmanned mining. Existing literature has studied the intelligent construction of coal mine enterprises from the path of intelligent technology support (Wang et al., 2020; Li et al., 2020), which has accelerated the integrated development of emerging technology and intelligent construction of coal mine. The difference of coal seam occurrence condition and technical level will affect the choice of production behavior strategy of coal mine enterprises, and coal mine enterprises will adjust their decision to maximize the utility. This paper uses evolutionary game model to analyze the dynamic adjustment of intelligent construction strategy in coal mine enterprises. Coal mining enterprises with bounded rationality may be unwilling to carry out intelligent construction or low efficiency intelligent construction due to short-sighted behavior. This will lead to the stagnation of the intelligent construction process of China's coal mining enterprises. It is necessary for the government to regulate and control the intelligent construction behavior of coal mining enterprises through policies. The existing research focuses on the technical support for the intelligent construction of coal mines (Matloo et al., 2021; Chen et al., 2021; Nguyen et al., 2020; Jo et al., 2019; Singh et al., 2018), and lacks the discussion on the management issues such as policy regulation in the intelligent construction of coal mining enterprises, which also shows the necessity and urgency of this research. The main aims of this study are to explore the following two management issues: a. What factors determine the behavior strategy of “intelligent construction” or “traditional production” adopted by coal mining enterprises? b. In the face of coal mining enterprises with different mining methods (such as open-pit coal mines and underground coal mines), how to guide coal mining enterprises to carry out intelligent construction through effective policy regulation? In order to answer the above two questions, this paper builds a Moran process stochastic evolutionary game model of coal mining enterprises based on the existing coal production capacity replacement policy. We then move on to calculate the probability of successful application of ‘intelligent construction’ strategy and ‘traditional production’ strategy. By comparing the probability of individual fixed point and the probability of neutral mutation, the dominant conditions of strategy under strong selection and weak selection are obtained. The strategy is expected to provide a scientific basis for policy makers to carry out accurate regulation of coal mining intelligent construction policy.

The rest of this paper is arranged as follows. The second section is a literature review on intelligent construction and evolutionary game. The third section is the methods and model. The fourth section is the solution and analysis of the model. The fifth section is case analysis. The sixth section is discussion. The seventh section is the conclusion.

2. Literature review

The research on the intelligent construction of enterprises mainly focuses on the real economy fields such as manufacturing and medical treatment. It mostly adopts the methods of structural equation model, case study and empirical analysis, which focuses on the research on the influencing factors (Goh, 2006), action mechanism (Bolak and Romanová, 2020; Wang et al., 2020) and realization path (Ma and Huang, 2021; Lacheheub and Maamri, 2016; Chowdary and Kuppili, 2021) of intelligent construction. The research on intelligent construction of coal mine is mainly concentrated in the field of engineering technology, focusing on intelligent technology development of coal mine (Fu et al., 2021), system construction (Agrawal et al., 2017), intelligent optimization (Xing et al., 2021; Laub, 1999), etc., which lacks the research on intelligent construction of coal mine enterprises from the perspective of management. The problem of promoting the intelligent construction of enterprises is actually manifested in the game process of strategy interaction of relevant stakeholders. Game theory is widely used in the behavioral countermeasures of enterprise intelligent construction. The main research results include: network security intelligent defense static game (Ma et al., 2020; Liu et al., 2020), technology research and development dynamic game (Guo et al., 2020), production scheduling repeated game (Wang et al., 2019). The above game models of intelligent construction of coal mining enterprises mostly focus on one-time choice (such as static game and dynamic game), or the overall planning framework based on high encounter ability (such as repeated game), which has not taken into account the continuous strategy adjustment of coal mining enterprises due to the changes of internal and external environment in the state of long-term symbiosis.

Aiming at the characteristics of mutual learning and adaptive adjustment of strategies among participants in groups, evolutionary game theory provides a reasonable analysis framework, which is widely used in environmental governance (da Silva Rocha and Salomão, 2019), low-carbon supply chain (Kang et al., 2019), energy security (Liu et al., 2015; Wang et al., 2020). Among them, for the construction of enterprise intelligence, research scholars use the classic evolutionary game model, which mostly focuses on cloud manufacturing services (Huo et al., 2021; Wang et al., 2020) and realization path (Lu et al., 2021; Litos et al., 2017), value co-creation (Li et al., 2021), etc. However, there are still two practical characteristics in the behavior decision of intelligent construction in coal mining enterprises: on the one hand, the number of coal mining enterprises are limited, and the classical evolutionary game theory is based on the overall infinite adaptive strategy adjustment; On the other hand, the changeable geological environment such as rock burst, gas outburst and water permeability brings uncertainty to the intelligent construction of coal mine enterprises, while the classical evolutionary game theory does not consider the influence of uncertain environment on equilibrium. Based on this, the dynamic model of stochastic evolutionary game in limited group environment is proposed. In the stochastic evolution dynamic model, individual behavior selection and strategy evolution in a limited group are regarded as a stochastic process, mainly including pairwise comparison process,
Wright-Fisher process and Moran process (Corradi and Sarin, 2000). Among them, the Moran process is the most widely used stochastic process mechanism in research and application, which describes the evolutionary dynamics of a limited group (Traulsen et al., 2008). Theoretical research on Moran process is relatively abundant. Corradi et al. used the method of continuous approximation to analyze the changing trend of individual selection ratios in stochastic evolutionary games over time; Nowak et al. (2004) deduced the probability of population change in the time interval before and after Moran process. In addition, existing researchers have widely applied the stochastic evolutionary game model based on Moran process to the fields of management to solve practical problems, mainly including green technology innovation (Zhang and Li, 2020), emergency counter-terrorism (Wu et al., 2020), and emotional evolution (Dai et al., 2021; Dong et al., 2021). But there is little involved in the analysis of intelligent construction of coal mining enterprises under the random disturbance of uncertain factors.

Aiming at the uncertainty brought by the changeable underground geological environment to the intelligent construction of coal mining enterprises, this paper extracts two basic characteristics and assumptions of long-term evolution and external randomness of the intelligent construction of coal mining enterprises. The stochastic evolution model of intelligent construction of coal mining enterprises analyzes the boundary conditions for coal mining enterprises to choose the strategy of "intelligent construction", so as to achieve the analysis of intelligent construction of existing enterprises.

3. Methods and model

It is assumed that the number of coal mining enterprises is limited and the mixture is uniform. The intelligent construction of coal mine mainly refers to the reduction of underground personnel and improvement of efficiency through the innovation of mining technology and equipment. Referring to the assumption of enterprise homogeneity in technological innovation research (Dinopoulos and Segerstrom, 1999), there are N homogeneous coal mining enterprises, and coal mining enterprises are faced with a feasible strategy set (intelligent construction, traditional production), denoted as (I, T). The net payoffs of coal mining enterprises under the traditional production mode is \( P_i > 0 \). The implementation of intelligent construction can enable enterprises to mine safely and improve the core competitiveness of enterprises. The benefit brought by intelligent construction is \( v(y) > 0 \), and the cost of intelligent construction is \( c(y) > 0 \). For any two enterprises, when the coal mining enterprises all choose the "intelligent construction" strategy, the change in their respective payoffs is \( v - c \). If the two coal mining enterprises choose different strategies, due to the gap in the level of intelligent production among two enterprises, the government implements the capacity replacement policy for coal mining enterprises to promote the adjustment of coal industry structure and the withdrawal of backward production capacity. Let \( k(k > 1) \) be the intensity of capacity replacement. The capacity replacement is divided into equal replacement and reduction replacement. Equal replacement means that the capacity of new (modified and expanded) projects is equal to the eliminated backward or excess capacity \( (k = 1) \); Reduced replacement means that the capacity of new (reconstruction and expansion) projects is greater than the obsolete backward or excess capacity \( (k > 1) \). The \( \theta(\theta > 0) \) is the proportion of coal mine capacity increase. According to the 'Administrative Measures for Coal Mine Production Capacity', a qualified unit evaluates the capacity of each system link of the coal mine. If the maximum actual capacity is higher than its certified capacity, the approved legally registered capacity will be increased to the maximum capacity of the system. 'construction first, then evaluation' is the main feature of the increase in production capacity. The change of the net payoffs of enterprise \( i \) is \( (1 + \theta)v - c \). Enterprise 3 – 1 saves the cost of intelligent construction because it does not carry out intelligent construction, which can be regarded as the positive benefit obtained by the enterprise \( 3 – i \). The decrease of market share leads to the decrease of its net payoffs, denoted as \( kIP \), then the amount of change in the net payoffs of enterprise \( 3 – i \) is \( c – kIP \). If both enterprises adopt the "traditional production" strategy and refer to the existing policies, the government will impose penalties on coal mining companies to stop production in order to accelerate the progress of intelligent construction until they complete the intelligent transformation, and then the change in enterprise payoff is \( – P \). The effectiveness of intelligent supervision of coal mining enterprises, in this case, the payoffs of coal mining enterprises is the lowest compared with the other three cases Table 1. The utility function of coal mining enterprises not only depends on the expected payoffs of adopting different production behavior strategies, but also is affected by many uncertain stochastic factors. The external changeable geological environment makes the choice of behavior strategy of coal mining enterprises uncertain.

Among the coal mining enterprises with a number of \( N \), it is assumed that the number of enterprises adopting the "intelligent construction" behavior strategy is \( i \), and the other enterprises adopt the "traditional production" strategy. The expected payoffs of enterprises adopting these two strategies can be expressed by eqs. (1) and (2):

\[
E_i = \frac{v - c}{N} (i - 1) + \frac{(1 + \theta) v - c}{N} (N - i) \quad \text{for } i = 1, 2, ..., N - 1. \quad (1)
\]

\[
E_i = \frac{c - kIP}{N} (i + (N - i - 1)) \quad \text{for } i = 1, 2, ..., N - 1. \quad (2)
\]

In the evolutionary game dynamics framework, fitness depends on the expected payoff. In the stochastic evolutionary game model, coal mining enterprises need to consider stochastic disturbance factors in addition to expected payoffs when choosing production behavior strategies. Strategy selection based on Moran process needs to introduce an exogenous variable, namely selection strength. Among them, at high selection strength, utility is highly correlated with expected payoff; at low selection strength, utility depends almost entirely on other external stochastic interference factors; between the two states, for convenience, utility is set to increase with selection strength uniform variation. The participant utility function based on the stochastic evolutionary game Moran process is constructed as a linear function in Eq. (3):

\[
F_i = 1 - \omega + \omega E_i, \quad G_i = 1 - \omega + \omega E_i, \quad 0 \leq \omega \leq 1. \quad (3)
\]

Based on the Moran process analysis, the probability of increasing one individual adopting the "intelligent construction" strategy is \( \frac{N - i}{N} \). After the evolution of each time step, the number of individuals adopting the "intelligent construction" strategy may be reduced by one, unchanged or increased by one. The transition probabilities are shown in eqs. (4), (5), and (6):

\[
P_{i+1} = \frac{\frac{N - i}{N} G_i}{\frac{N - i}{N} G_i + \frac{i}{N} F_i} \times \frac{N - i}{N}. \quad (4)
\]

\[
P_{i+1} = \frac{i}{\frac{N - i}{N} F_i + \frac{i}{N} G_i} \times \frac{i}{N}. \quad (5)
\]

Table 1. 2 × 2 symmetric stochastic evolutionary game model between coal mining enterprises.

| \( i \) | \( T \) | \( I \) |
|-------|-------|-------|
| \( v - c, v - c \) | \( (1 + \theta)v - c, c - kIP \) |
| \( c - kIP, (1 + \theta)v - c \) | \( -P, -P \) |

2 http://www.ccoalnews.com/news/202109/26/c149337.html.
The production behavior of coal mining enterprises is easily disturbed by stochastic factors, such as the harsh underground geological environment. At this time, stochastic factors occupy the dominant position of enterprise behavior decision-making, that is, the weak selection process when selecting intensity $\omega \to 0$.

Substitute Eq. (3) into eqs. (9) and (10), and carry out Taylor expansion at $\omega \to 0$. We can obtain the fixed probability of the two strategies under weak selection as shown in Eqs. (11) and (12):

\[
\rho_i = \frac{1}{N} \omega e^{\left[ (3 + 2\theta)v - 4c + (k\theta + 2)P \right] N + (k\theta - 1)P - (3 + \theta)v + 2c].
\]

\[
\rho_f = \frac{1}{N} \omega e^{\left[ (3 + 2\theta)v - 4c + (k\theta + 2)P \right] N + (k\theta - 1)P - (3 + \theta)v + 4c].
\]

According to the study of Taylor, the fixed point probability $\frac{1}{N}$ of neutral mutation is taken as the benchmark to study the strategy selection of individuals in a limited group. If $\rho_f > \frac{1}{N}, \rho_f < \frac{1}{N}$, strategy $f$ will replace strategy $T$. On the contrary, if $\rho_f > \frac{1}{N}, \rho_f < \frac{1}{N}$, strategy $T$ will replace strategy $f$.

Based on the above criteria of neutral drift theorem, through the analytical eqs. (11) and (12), the evolutionary equilibrium of production behavior of coal mining enterprises dominated by stochastic factors is obtained, as shown in proposition 1. The specific proof process is shown in the appendix.

Proposition 1. (dominated by stochastic factors): when the intelligent construction of coal mining enterprises is dominated by stochastic factors, if $(3 + \theta)v > 5c - (2k\theta + 1)P$, then $\rho_f > \frac{1}{N}, \rho_f < \frac{1}{N}$, coal mining enterprises choose the strategy of "intelligent construction"; If $(3 + \theta)v < 4c - (k\theta + 2)P$, then $\rho_f > \frac{1}{N}, \rho_f < \frac{1}{N}$, coal mining enterprises choose the "traditional production" strategy.

It can be seen from Proposition 1 that when the stochastic factors dominate, with the increase of intelligent construction benefits $v$, capacity replacement intensity $k$ and intelligent coal mine capacity increase ratio $\theta$, as well as the reduction of intelligent construction cost $c$, coal mining enterprises will adopt the "intelligent construction" strategy; On the contrary, due to the poor cost and benefit of intelligent construction, coal mining enterprises choose the "traditional production" strategy.

China has a huge number of coal mines, mainly underground coal mines. Affected by rock burst, surrounding rock strength and mining depth, underground coal mining has a high degree of uncertainty.

4. Analysis of evolutionary equilibrium results

4.1. Decision analysis dominated by stochastic factors

The behavior of coal mining enterprises is easily disturbed by stochastic factors, such as the harsh underground geological environment. At this time, stochastic factors occupy the dominant position of enterprise behavior decision-making, that is, the weak selection process when selecting intensity $\omega \to 0$.

Substitute Eq. (3) into eqs. (9) and (10), and carry out Taylor expansion at $\omega \to 0$. We can obtain the fixed probability of the two strategies under weak selection as shown in Eqs. (11) and (12):

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\]

\[
\rho_f = \frac{1}{N} \omega e^{\left[ (3 + 2\theta)v - 4c + (k\theta + 2)P \right] N + (k\theta - 1)P - (3 + \theta)v + 4c].
\]
stage of coal mining enterprises, for the underground coal mines dominated by stochastic factors, the intelligent process can be effectively promoted by increasing the capacity replacement intensity \( k \) and the capacity increase proportion \( \theta \) of intelligent coal mine as well as the reduction of intelligent construction cost \( c \).

In addition, due to different strategies, the choice is also related to the size of \( N \). For a more intuitive analysis, let \( R_t = N\rho_t \) denote the number of coal mining enterprises adopting the strategy of “intelligent construction”; let \( R_t = N\rho_t \) denote the number of coal mining enterprises adopting the strategy of “traditional production”. If \( R_t > 1, R_t < 1 \), “intelligent construction” will become the evolution and stability strategy of coal mining enterprise group; if \( R_t < 1, R_t > 1 \), then “traditional production” will become the evolution and stability strategy of coal mining enterprise group. If \( R_t > 1, R_t > 1 \), the two strategies will become a mixed equilibrium state of coexistence.

4.2. Decision analysis under the dominance of expected payoffs

When coal mining enterprises make rational decisions based on the cost-benefit of behavioral decision-making itself, it is the strong selection process, that is, \( \omega = 1 \). At this time, the stochastic interference of uncertain factors on the production behavior of enterprises is relatively small. Given the number \( i \) of enterprises adopting “intelligent construction” at a certain time, the increase or decrease of the number of enterprises adopting “intelligent construction” strategy is judged by comparing the difference between the utility functions of the two strategies. The difference between “intelligent construction” and “traditional production” strategies is expressed as Eq. (13):

\[
h_i = F_i - G_i, \quad i = 1, 2, \ldots, N - 1. \tag{13}
\]

Substitute Eqs. (1), (2), and (3) into (13) to get eqs. (14) and (15):

\[
h_1 = F_1 - G_1 = \frac{(N - 1)((1 + \theta)v - c + p) - P - c + k\theta P}{N - 1}, \tag{14}
\]

\[
h_{N-1} = F_{N-1} - G_{N-1} = \frac{(N - 1)(v - 2c + k\theta P) + \theta v}{N - 1}. \tag{15}
\]

According to the theory of (Taylor et al., 2004), the definition of evolutionary stable strategy is that a few people in the group adopt the invasion strategy and are repelled, and the existing strategy of the group is called evolutionary stable strategy. The specific criteria for judging evolutionary stability strategies are:

① If \( h_i > 0 \), the choice behavior supports the "intelligent construction" strategy and invades the "traditional production" strategy; Otherwise, if \( h_{N-1} < 0 \), the choice behavior supports the "traditional production" strategy and invades the "intelligent construction" strategy;

② If \( h_i > 0 \) and \( h_{N-1} > 0 \), the "intelligent construction" strategy will replace the ‘traditional production’ strategy and become an evolutionary stable strategy;

③ If \( h_i < 0 \) and \( h_{N-1} < 0 \), the "traditional production" strategy will replace the ‘intelligent construction’ strategy and become an evolutionary stable strategy;

④ If \( h_i > 0 \) and \( h_{N-1} < 0 \), the two strategies coexist, and the mixed strategy will become an evolutionary stable strategy;

⑤ If \( h_i < 0 \), the “traditional production” strategy becomes a Nash equilibrium, and if \( h_{N-1} > 0 \), the “intelligent construction” becomes a Nash equilibrium.

According to the above judgment criteria, through the analysis of eqs. (14) and (15), the evolutionary equilibrium of the production behavior of coal mining enterprises under the dominance of expected payoffs is obtained, as shown in Proposition 2, and the specific proof process is detailed in the appendix.

Proposition 2. (dominated by expected payoffs) When coal mining enterprises make production behavior decisions based on expected payoffs, if \( v \in (\frac{P}{C_0}, 2c - k\theta P) \), there is a critical value \( N_0 = \frac{P}{C_0} + 1 \). When the number of coal mining enterprises is \( N < N_0 \), the “intelligent construction” strategy will become an evolutionary stable strategy. When \( N > N_0 \), the mixed equilibrium of the two strategies becomes an evolutionary stable strategy. If \( v \in (2c - k\theta P, \infty) \), for any \( N \), “intelligent construction” strategy will become an evolutionary stable strategy.

At present, China’s coal mine intelligent construction is in the primary cultivation stage. The cost-benefit of intelligent construction is low and the economic benefit is not significant. According to Proposition 2, when the production behavior of coal mining enterprises is dominated by expected payoffs, the intelligent cultivation process of coal mining enterprises can be promoted by reducing the number of coal mining enterprises; With the gradual maturity of intelligent technology and system, the payoff of enterprise intelligent construction is gradually increasing. Adopting the strategy of “intelligent construction” will become the consensus of coal mining enterprises. Compared with underground coal mines, open-pit coal mines have the advantages of good safety conditions, high resource recovery rate and large production scale due to the shallow burial of coal seams and less constraints by environmental conditions. There are less uncertain factors in the process of coal mining, and the production decision-making is mainly based on expected income. Proposition 2 shows that for open-pit coal mines dominated by expected payoffs, controlling the number of open-pit coal mines is conducive to promoting their intelligent cultivation process. This conclusion has been applied in China’s real production. In the production and construction of open-pit coal mines in various places, there is a phenomenon that the coal mine capacity cannot be effectively released due to the problem of land acquisition. For example, some areas suitable for the construction of large open-pit mines are artificially divided. A small number of open-pit mines are formed, resulting in a short production line length, and the capacity of coal mines cannot be greatly improved, which hinders the release of advanced production capacity of open-pit coal mines. Improving the concentration of open-pit mining coal industry can effectively promote the intelligent cultivation process of open-pit coal mines.

5. Case analysis based on the intelligent construction of coal mining enterprises

In order to verify and display more abundant theoretical analysis results, this paper takes Zuoyun Changchun Xing Coal Industry Co., Ltd. (hereinafter referred to as “Changchun Xing Coal Mine”), a coal mine of Shanchi Coal International Energy Group Co., Ltd., as the data source for case analysis. Changchun Xing Coal Mine was established in 2012 with a total investment of 1.44 billion yuan, a mine field area of 19.8563 square kilometers, 346 million tons of geological reserves, 225 million tons of recoverable reserves, a designed production capacity of 2.4 million tons per year, and an annual profit of about 250 million yuan. The mine actively carried out the intelligent construction of coal mines, and built the first “cloud-controlled mine” of coal mines through the self-developed “mobile Internet + coal mine cloud” platform, which has become an intelligent demonstration mine. In 2017, Changchun Xing Coal Mine signed the ‘Coal Capacity Replacement Index Transaction Agreement’ with the Hunan Provincial Coal Administration Bureau. The production capacity will be increased from 2.4 million tons/year to 4.5 million tons/year, so \( \theta = 0.875 \). The withdrawal of backward production capacity in the capacity replacement scheme often involves multiple enterprises. According to the assumption of enterprise homogeneity, it can be converted to one enterprise in equal quantities for analysis. Referring to the investment standard for intelligent transformation of existing stock coal mines, the mine field structure and hydrogeological type of Changchun Xing coal mine are simple, so the intelligent construction cost of the mine is about 100 million yuan. The investment

3 https://www.sohu.com/a/273489082_693867.

4 https://www.sohu.com/a/480357336_121123789.
return cycle of coal mine intelligent construction is long, and the payoffs of coal mine intelligent construction changes with the change of coal mine intelligent construction process. In the short term, the economic benefits generated by reducing personnel and improving efficiency are difficult to offset a large amount of infrastructure construction costs in the early stage. With the advancement of intelligent process and the increase of enterprise core competitiveness and goodwill, the benefits of coal mine intelligent construction gradually increases. At the same time, the capacity replacement intensity $k$ will be adjusted with the change of the actual demand of the enterprise and the overall intelligent layout. According to the existing policies\(^5\), the reduction replacement proportion of coal mining enterprises can reach up to 300%, so $k = \frac{3}{2}$ and $\theta = \frac{4}{3}$. The following will make a sensitivity analysis on the benefits of coal mine intelligent construction $v$ and capacity replacement intensity $k$.

5.1. Decision analysis under the domination of stochastic factors

In the decision-making process of production behavior of coal mining enterprises, if stochastic factors such as geological environment dominate, the weak selection strength is set to $\omega = 0.00001$. Based on the difference in capacity replacement method and ratio, set $k = 1$ and $k = 3$ respectively. When $k = 1$, the government implements an equivalent replacement policy for coal mining enterprises. Considering that the benefit of intelligent construction of coal mining enterprises is small, $v < \frac{4c - (3k + 1)P}{k + 2} \approx 2.7$, the specific payoffs of intelligent construction of coal mining enterprises is set to $v = 2.5$; when the benefit of intelligent construction of coal mining enterprises is large, $v > \frac{4c - (3k + 1)P}{k + 2} \approx 4.7$, the specific benefit of intelligent construction of coal mining enterprises is set as $v = 10$. According to Eqs. (10) and (11), the influence of $v$ and $k$ of coal mining enterprises on the production behavior strategy of coal mining enterprises can be analyzed. On the basis of the value $v$ of the above-mentioned intelligent construction payoffs of coal mining enterprises, continue to increase the capacity replacement intensity $k$. When $k = 3$, the government implements the reduction replacement policy for coal mining enterprises, and the corresponding strategy selection of coal mining enterprises is shown in Figure 1.

When the benefit of intelligent construction of coal mine is small, i.e. $v = 2.5$ and $k = 1$, it can be seen from Figure 1 that the equilibrium condition $(3 + \theta)v > 4c - (k\theta + 2)P$ in proposition 1 is satisfied and there is $R_2 > 1$, $R_1 < 1$. At this time, "traditional production" becomes an evolutionary stability strategy; To increase the intensity of capacity replacement, i.e. $k = 3$, at this time, $R_1 > 1$, $R_2 < 1$, "intelligent construction" has become an evolutionary stability strategy. Therefore, during the cultivation period of intelligent construction of coal mining enterprises, for underground coal mines dominated by stochastic factors, increasing the intensity of capacity replacement can effectively promote the process of intelligent construction. When the benefit of intelligent construction of coal mine $v$ is large, $v = 10$ and $k = 1$ satisfy the equilibrium condition $(3 + \theta)v > 5c - (2k\theta + 1)P$ in proposition 1.
with \( R_1 > 1, R_T < 1 \), then "intelligent construction" becomes an evolutionary stability strategy. To increase the intensity of capacity replacement, \( k = 3 \), there is still \( R_1 > 1 \) \( R_T < 1 \), and "intelligent construction" is an evolutionary stability strategy. Therefore, for underground coal mines dominated by stochastic factors, with the improvement of the cost and benefits of intelligent construction, the "intelligent construction" strategy will become a general consensus of coal mining enterprises.

5.2. Decision analysis under the dominance of expected payoffs

Coal mining enterprises make decisions based on the expected payoffs of different strategies, and the strong selection strength is set to \( \omega_d = 1 \). Similarly to Section 5.1, considering the four situations: \( k = 1, k = 3, \nu = 2.5, \nu = 10 \). According to eqs. (14) and (15), the analysis of the production behavior strategy selection of coal mining enterprises under the dominance of expected payoffs is shown in Figure 2.

It can be seen from Figure 2 that under the dominance of expected payoffs, when the intelligent construction benefits \( \nu \) of coal mining enterprises is small, i.e. \( \nu = 2.5, k = 1 \), it satisfies \( \nu < \frac{2(c-t)}{C_0} \). At this time, the mixed strategy becomes an evolutionary stable strategy and we continue to increase the capacity replacement intensity, i.e. \( k = 3, \nu \in \left( \frac{2(c-t)}{C_0}, 2 - \frac{2(c-t)}{C_0} \right) \) is satisfied, and there is a critical value \( N_0 = 4 \) at this time. When the number of coal mining enterprises is \( N < N_0 \), \( R_1 > 0 \), \( h_{N,1} > 0 \) is satisfied, and "intelligent construction" is an evolutionary stable strategy. When the number of coal mining enterprises is \( N \geq N_0 \), it satisfies \( h_1 > 0, h_{N,1} < 0 \), and the mixed strategy is an evolutionary stable strategy. When the benefits of intelligent construction of coal mining enterprises is large, i.e. \( \nu = 10 \), regardless of \( k = 1 \) or \( k = 3 \), it satisfies \( \nu > 2c - kP \). At this time, there is \( h_1 > 0 \) \( h_{N,1} > 0 \), and "intelligent construction" is an evolutionary and stable strategy. Therefore, in the intelligent cultivation period of coal mining enterprises, there is a critical quantity scale \( N_0 \) for open-pit coal mines dominated by expected payoffs. By reducing the number of mining rights and improving the concentration of open-pit coal mining industry, the willingness of intelligent construction of open-pit coal mining enterprises can be improved. With the improvement of the cost-benefit of intelligent construction, "intelligent construction" strategy will become a general consensus among open-pit coal mining enterprises.

6. Discussion

The intelligent construction of coal mining enterprises is an important way to realize the high-quality development of the coal industry. Existing literatures (Matloob, S. et al., 2021; Li et al., 2021) mainly focus on intelligent technical support for enterprises from the perspective of engineering technology, and most models are based on the assumption of infinite population. This ignores the following two points. a. Although the existing research has laid a good foundation for the improvement of intelligent technology, coal mining enterprises are not necessarily willing to adopt these technologies, because coal mining enterprises with bounded rationality may have short-sighted behaviors such as speculation, and efficient and accurate management measures are also essential. b. The infinite population hypothesis in the existing research seems to be close to the mining status of a large number of underground coal mines. For a small number of open-pit coal mines, the conclusions drawn from the traditional evolutionary game model may be less applicable, which requires a more realistic limited population hypothesis. The above two points are also the differences between this paper and the existing research. From the perspective of management, this paper takes full account of the limited population characteristics of coal mining enterprises and studies the intelligent construction of coal mining enterprises based on the limited population hypothesis. The conclusions have certain guiding significance for the actual production of the coal industry.

Firstly, this paper finds that the guiding effect of capacity replacement policy on the intelligent construction of coal mining enterprises is dynamic, and the government should implement differentiated capacity replacement policy according to the different stages of enterprise intelligent construction. During the cultivation period of intelligent construction, coal mining enterprises should be guided to adopt intelligent construction strategy by increasing the intensity of capacity reduction replacement, which has also been proved to be effective. However, the greater capacity replacement may bring some negative effects, such as the employee placement of coal mining enterprises that have closed down and exited. In other words, a stronger capacity replacement policy may bring higher policy costs. With the continuous advancement of the intelligent process, the intelligent system tends to be mature. At this time, the government should appropriately relax the capacity replacement policy (such as the implementation of equal capacity replacement) and accelerate the promotion and application of intelligent technology to improve the cost-benefit of intelligent construction of coal mining enterprises.

Secondly, for open-pit coal mines, the number of coal mines is also an important factor affecting the choice of enterprise strategy. Combined with the conclusion of this study, the strategy selection of open-pit coal mine varies greatly under different quantity conditions. During the cultivation period of intelligent construction, a large number of open-pit coal mines may weaken the effect of capacity replacement policy. The reason is that land acquisition for open-pit coal mines is difficult due to the impact of environmental protection policies, which has a serious impact on the release of high-quality production capacity of open-pit coal mines. In the case of a large number of open-pit coal mines, this negative effect is amplified, and the willingness of intelligent construction of open-pit coal mines is low. For the government, it should reduce the negative effect caused by the excessive number of open-pit coal mines by reducing the number of mining rights and improving the concentration of open-pit coal mining industry. Specifically, this conclusion can be applied to production practice by building large-scale intensive open-pit coal mines and integrating small and medium-sized open-pit coal mines. This also provides policy guidance for the intelligent construction solutions of open-pit coal mine and the promotion of Industry 5.0.

Finally, this paper has also some limitations. The linear function is used to describe the strategy selection process of participants in the situation of strong selection or weak selection. In the future, the adaptability of the traditional linear function in the two situations can be considered. At the same time, this paper analyzes the behavior evolution of participants based on two symmetrical strategies. In the future, we can consider the changes of participants’ strategy choice when there are more than two and asymmetric strategy spaces.

7. Conclusion

China’s energy will remain a structure dominated by coal and supplemented by other energy sources for a long time to come. Realizing the intelligent mining of coal resources is the strategic task and the important way for the high-quality development of China's coal industry. The changeable geological environment factors in coal mine bring uncertainty to coal mine safety production. Considering the high uncertainty and the number of coal mine enterprise groups, this paper constructs a stochastic evolution game model of intelligent construction of coal mine enterprises based on Moran process, and studies the strategy of "intelligent construction" or "traditional production" selected by coal mine enterprises. The research shows that external stochastic factors, the number and scale of enterprises, the intensity of capacity replacement and the cost-benefit of intelligent construction are the main factors affecting the intelligent construction behavior of coal mining enterprises. When the intelligent construction of coal mining enterprises is in the cultivation period, the intelligent construction of underground coal mines dominated by stochastic factors can be effectively promoted by increasing the intensity of capacity reduction replacement; For the open-pit coal mine
dominated by expected payoffs, reducing the number of mining rights and improving the concentration of open-pit coal mining industry will have a better effect on promoting its intelligent cultivation process. When the intelligent construction of coal mining enterprises is in the mature stage, with the improvement of the cost and benefits of intelligent construction, “intelligent construction” strategy will become a general consensus of coal mining enterprises.

Compared with the existing literature, this paper has the following two innovations: a. The existing research is mainly based on the assumption of infinite population, which is close to the mining status of a large number of underground coal mines. However, it deviates greatly from the current mining situation of a small number of open-pit coal mines. In this paper, the limited population hypothesis in the existing research is relaxed, and the research based on the limited population hypothesis is more close to the production practice of open-pit coal mine. b. This paper takes bounded rationality of the game players into account hypothesis is more close to the production practice of open-pit coal mine.

The same can be proved, when the production behavior of coal mining enterprises is dominated by stochastic factors, if the enterprise chooses the “intelligent construction” strategy, it meets when the production behavior of coal mining enterprises is dominated by expected payoffs, if the “intelligent construction” strategy is an evolutionary stable strategy. When China’s coal mines are mainly underground coal mines (about 90% of the total), and there are about 5,000 coal mines in stock. When the number of coal mining enterprises N is sufficiently large, there is (3 + 2θ)v − 4c + (kθ + 2)P > 0, namely (3 + θ)v > 4c − (kθ + 2)P; When ρ1 < 1 N there is (3 + θ)v > 5c − (2kθ + 1)P. Due to (5/3 + θ)1/(3 + θ)0 > θ, so enterprises choose the strategy of “intelligent construction”. The same can be proved, when (3 + 2θ)v < 4c − (kθ + 2)P, we obtain ρT > 1 N, so enterprises choose “traditional production” strategy.

Proposition 1: When the production behavior of coal mining enterprises is dominated by stochastic factors, if the enterprise chooses the “intelligent construction” strategy, it meets ρ1 > 1 N, ρT < 1 N. According to Eqs. (11) and (12), Set a = (3 + 2θ)v − 4c + (kθ + 2)P, b = (kθ − 1)P − (3 + θ)v + 2c, l = 5c − (2kθ + 1)P − (3 + θ)v, m = (3 − θ)v + (kθ + 2)P − 4c, Then Eqs. (11) and (12) can be expressed as:

\[
\rho_1 = \frac{1}{N} + \frac{\omega}{6N}[aN + b],
\]

\[
\rho_T = \frac{1}{N} + \frac{\omega}{6N}[m].
\]

So ρ1 > 1 N is equals to aN + b > 0, That is, the inequality should satisfy condition (3 + 2θ)v − 4c + (kθ + 2)P + (5kθ + 1 − 3θ)P/3 > 0. Since China’s coal mines are mainly underground coal mines (about 90% of the total), and there are about 5,000 coal mines in stock. When the number of coal mining enterprises N is sufficiently large, there is (3 + 2θ)v − 4c + (kθ + 2)P > 0, namely (3 + θ)v > 4c − (kθ + 2)P; When ρ1 < 1 N there is (3 + θ)v > 5c − (2kθ + 1)P. Due to (5/3 + θ)1/(3 + θ)0 > θ, so enterprises choose the strategy of “intelligent construction”. The same can be proved, when (3 + 2θ)v < 4c − (kθ + 2)P, we obtain ρT > 1 N, so enterprises choose “traditional production” strategy.

Proposition 2: When the production behavior of coal mining enterprises is dominated by expected payoffs, if the “intelligent construction” strategy is an evolutionary stable strategy, h1 > 0 and hN−1 > 0 is satisfied. Firstly, since (1 + θ)v − c + P > 0, inference from h1 > 0 to get N < P + kθP/1 + θcP + 1. Secondly, when v − 2c + kθP < 0, that is v < 2c − kθP, inference from hN−1 > 0 to get N < \(\frac{\theta}{2c - k\theta P}\). Substitute N = 2 into eqs. (14) and (15) to get h1 = hN−1 = (1 + θ)v − 2c + kθP. When (1 + θ)v − 2c + kθP > 0, that is v > \(\frac{2c - k\theta P}{1 + \theta c}\), h1 is always greater than 0. So when v ∈ \((\frac{2c - k\theta P}{1 + \theta c}, +\infty)\), for N ∈ \((\frac{\theta}{2c - k\theta P}, +\infty)\), there is hN−1 > 0. The strategy of “intelligent construction” is an evolutionary and stable strategy. When N ∈ \((\frac{\theta}{2c - k\theta P} + 1, \infty)\), there is hN−1 < 0, mixed strategies become evolutionary stable strategies. When v − 2c + kθP > 0, that is v > 2c − kθP, for any N ≥ 2, there is h1 > 0 and hN−1 > 0. The “intelligent construction” strategy is an evolutionary stable strategy.

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The authors declare no conflict of interest.

Additional information

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