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Effectiveness research on the multi-player evolutionary game of coal-mine safety regulation in China based on system dynamics

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ABSTRACT

Coal-mine safety regulation is an important approach to ensure safe production in the mining industry. The existing literature on China's coal-mine safety regulation focuses mainly on statically analysing the game between two stakeholders and neglects the dynamic process of game playing under bounded rationality. Moreover, when there are a number of coal-mining enterprises, there are different interest demands between them in the context of regulation. Therefore, this paper explores the use of evolutionary game theory to describe the long-term dynamic process of multi-player game playing in coal-mine safety regulation under the condition of bounded rationality. Furthermore, the multi-player evolutionary game is simulated by adopting system dynamics to analyse the implementation effect of different penalty strategies on the game process and game equilibrium. The simulation results are as follows. First, when the penalty strategy is static payment, the strategy selections of the stakeholders fluctuate repeatedly. Moreover, increasing the penalties can quickly control the occurrence of coal-mine enterprises' illegal behaviours in the short term, but in the long term, it can increase the fluctuation of coal-mine enterprises' illegal behaviours and make the game process more difficult to control. Second, when the penalty strategy is dynamic payment, the dynamic penalty strategy can effectively restrain the fluctuations existing in the game play and stabilize the game, reducing the safety risks caused by uncertainty. Moreover, the stable state and equilibrium values are not affected by the initial value changes. The application of system dynamics when simulating the multi-player game process is an effective way to analyse the implementation effects of different penalty strategies, which provides a more effective solution to the study of complex multi-player game problems.

1. Introduction

China is the largest underground coal producer and coal consumer in the world and has the largest record of fatalities in the coal-mining industry (Liu et al., 2017). Currently, while the safety performance of coal mines in China has improved overwhelmingly year after year (Liu et al., 2016, 2017), the industry still has an appalling record of fatalities. Mining remains one of the most hazardous occupations in China, and miners are exposed to hazards well in excess of those encountered by people who work in other occupations (Liu and Li, 2014; Nieto et al., 2014; Liu et al., 2016). Moreover, underground coal mining is recognized worldwide as one of the riskiest operations (Lama and Bodziony, 1998; Sari et al., 2004, 2009; Duzgun and Einstein, 2004; Duzgun, 2005; Greyson et al., 2009; Maiti and Khanzode, 2009; Paul, 2009; Khanzode et al., 2011; Saleh and Cummings, 2011; Onder et al., 2014; Mahdevari et al., 2014). Therefore, coal-mine safety remains one of the most critical outstanding problems in China.

Exploring the causes of China's appalling record of fatalities in the coal-mining industry, its complicated geological conditions, the predominance of underground mining, the insufficient skills of miners, etc., are all factors that contribute to the frequent and catastrophic nature of fatal mining accidents (Geng and Saleh, 2015). Nevertheless, the underlying cause of all of these factors is poor safety management (Liu and Li, 2013; Mahdevari et al., 2014). The safety management of coal mines in China primarily includes the government's external regulations and private enterprise's internal governance. Currently, China has formed a comprehensive, sophisticated and separate legal regime to regulate coal-mine safety (Xiao and Li, 2006; Wang, 2006; Xiao et al., 2008; Yan, 2009; Xiao, 2010; Deng and Wang 2013; Liu and Li, 2013; Huang, 2013; Tang, 2014; Liu et al., 2015). Before 1998, China's administrative agencies for regulating coal-mine safety had been changed frequently and repeatedly. Thus, at the end of 1999, the Chinese

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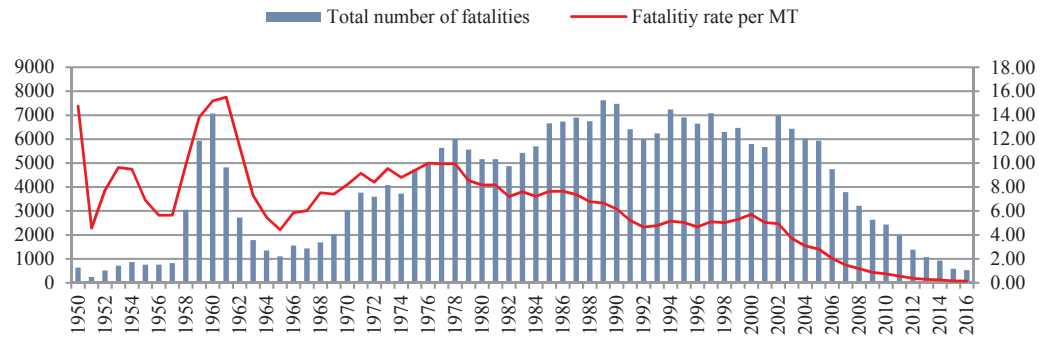

Fig. 1. China's fluctuations in coal-mine safety performance from 1950 to 2016. Note: The People's Republic of China was founded on October 1st, 1949. Source: China Coal Industry Statistical Yearbook (2015) and the website of the State Administration of Coal Mine Safety (SACMA).

government began to fundamentally reform its coal-mine safety regulation system (Geng and Saleh, 2015). The frequent and repeated changes of administrative agencies prior to this reform explain, at least in part, the fluctuations in China's coal-mine safety performance from 1950 to 2016 (Fig. 1). Moreover, multiple scholars from China and elsewhere have studied the existing problems of China's poor coal-mine safety performance from the perspective of governmental safety regulation. Some scholars have argued that coal-mine safety performance, such as accident frequency and extent of injury in the workplace, exhibits an obvious correlation with the strength of governmental safety regulations and that the government should strengthen the safety regulations governing coal mines (Lewis-Beck and Alford, 1980; Grey and Scholz, 1993; William, 2001; Grey and Mendeloff, 2005; Lu and Shang, 2005; Xiao, et al., 2008; Qin, 2013). However, other scholars have put forward objections to this conclusion, arguing that governmental safety regulations are ineffective and even hinder the development of the coal-mining industry (Viscusi, 1979; Baggs, et al., 2003; Wright, 2004). In regulatory terms, the coal-mining industry has invariably been regarded as a special case. The severity and distinctiveness of the hazards the industry confronts; its historically high level of work-related fatalities, injuries and disease; and its records of periodic disasters involving multiple fatalities have all resulted in a perception that mining should be treated differently from other industries. Influential stakeholders, in particular, have argued that specialized skills are needed for effective regulatory oversight and that, for this and other reasons, mining should be the subject of a separate regulatory regime (Gunningham, 2007).

In the current process of coal-mine safety regulation, the different interests and influences of the coal-mine safety regulators and coal-mine enterprises lead to conflicts of interest. As a result, although China has established a set of strict laws, regulations and rules on coal-mine safety, these laws and regulations are rarely implemented, which makes it difficult for coal-mine safety regulators to develop and implement effective regulation strategies, thereby to some extent contributing to China's poor coal-mine safety situation. Many scholars from China and elsewhere have studied the existing problems of China's poor coal-mining safety performance from different perspectives to explain the high incidence of accidents. In the existing literature on coal-mine safety regulation, game theory has been widely used to analyse the conflicts of interest. For example, Keiser (1980), Greenberg (1985) and Scholz (1991) discovered that regulation agencies and coal enterprises make trade-offs between public safety and personal interest throughout the regulation process; Li and Gao (2004) and Zhou and Zou (2005) noted that different interests and influences among the central government, local government and coal enterprises make coal-mine regulators' regulations less effective. Moreover, Chen and Lin (2006) and Zheng and Nie (2006) analysed the relationship between coal-mine regulators and the coal enterprise and concluded that the coal enterprise's inadequate safety investment was the real cause of the frequent accidents. In a similar vein, Lu and Zhao (2009) analysed the relationship between coal-mine regulators and the coal enterprise and proposed that the penalty for the coal enterprise's unlawful production should be strengthened in the short term. These studies provide a promising foundation to explain the high incidence of coal accidents in China. However, most existing research mainly focuses on statically analysing the game between two stakeholders and neglects the dynamic process of game play. In the process of coal-mine safety regulation, the players operate within bounded rationality, and their strategy selections are not always unchanged or static; instead, they change strategies dynamically by observing and comparing payoffs with others and adjusting their strategy selections. Moreover, when there are a number of coal-mine enterprises, there are different interests and demands between the coal-mine enterprises in response to regulation. Research is still needed to address the dynamic game involving multiple players under the condition of bounded rationality. Therefore, to help address this gap in the research, this paper explores the use of evolutionary game theory to describe the long-term dynamic process of multi-player game play in coal-mine safety regulation under bounded rationality. Furthermore, the multi-player evolutionary game is simulated by adopting system dynamics to analyse the implementation effect of different penalty strategies on the game process and game equilibrium.

The remainder of this paper is organized as follows. Section 2 introduces the multi-player evolutionary game analysis of coal-mine safety regulation. Section 3 presents the multi-player evolutionary game simulation based on system dynamics, including simulation model construction and strategy simulation results. Section 4 discusses the effectiveness of the static penalty strategy and dynamic penalty strategy. Finally, concluding remarks are presented in Section 5.

2. Multi-player evolutionary game analysis of coal-mine safety regulation

Evolutionary game theory was developed to overcome the disadvantages of traditional game theory when analysing the bounded rationality of players and the dynamic process of game playing. In the process of coal-mining safety regulation in China, the players are rationally bound, and they change their strategies dynamically by observing and comparing payoff with others and then adjusting their strategies. Therefore, evolutionary game theory is more suitable for studying the long-term dynamic game of bounded rational players in China's coal-mining safety regulation (Liu et al., 2015).

2.1. Game design and description

The coal-mine enterprise is assumed to be a rational economic man that makes strategy choices based on the principle of maximizing profit. Assuming that the coal-mine regulators' regulatory ability is strong enough, once illegal production enterprises are inspected, their violations would be discovered. Furthermore, there is no power rent-seeking in the process of law enforcement, and there are no coal-mine enterprises that escape punishment through various means.