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Research on the influencing factors in coal mine production safety based on the combination of DEMATEL and ISM

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ABSTRACT

In order to explore the influencing factors of mining safety in China and the related interactive mechanisms, this study calculates the statistics of 58 coal mine death accidents in Shandong, China, during the period from 2010 to 2014, and summarizes the accident causes to establish the index system of mining safety including 22 factors at 6 levels: organizational management, squad leaders, front-line workers, safety culture, underground environment and machines & equipment. Through questionnaire survey, the logical relations among various influencing factors are quantified. Afterwards, by combining DEMATEL and ISM, the influencing degree, influenced degree, centrality and causality of various influencing factors are calculated, and a hierarchical model is established for systematically analyzing the influencing factors of mining safety and the influencing mechanisms. According to the research results, safety supervision and safety philosophy are fundamental for mining safety; rules & regulations, safety climate, safety investment, communication, safety education, operational plan, safety consciousness, knowledge & skills and safety attitude are important factors, while leadership & coordination, individual characteristics, work satisfaction, safety awareness, knowledge & skills, adaptability, equipment & facilities, operating tools, safety device, operating condition, physical environment and geological conditions are direct causes that lead to accidents in coal mines. This study provides theoretical basis and methods to prevent coal mine accidents and improve mining safety.

0. Introduction

The poor microclimate conditions (confined operating space, insufficient fresh air, etc.) and heavy workload are the interactive factors leading to underground mine accident. Both research and experience indicate that most accidents are preventable (IAEA, 1996; Mahdevari et al., 2014; Toronea and Ciurea, 2014). However, safety management in China's mines is experience-based post-management, which does not prevent the occurrence of accidents from the root. Based on the 2011 Yearly Data of National Bureau of Statistics of China, Chen et al. (2013) concluded that 70% of world's total coal mine fatalities take place in China. In recent years, risk management was gradually gaining popularity in China's coal mine enterprises (Cao et al., 2012; Liu et al., 2016), which significantly improved production safety conditions in the mines. However, the reward-punishment methods, on which current risk management lays much importance, can hardly achieve desirable performances in modern mine production safety systems (Mosey, 2014; Leveson, 2011; Loiselle et al., 2016).

Modern coal mining safety systems are complex human-machine-environment-management systems with the common complex system characteristics: nonlinearity, emergency and feedback looping. Insufficient understanding of the complex system will result in overconfidence in risk management and poor result. Årstad and Aven (2017)proposed to use a cautious approach to understand the system's complexity. Based on nonlinear bifurcation theory, Yao (2010) pointed out that accident was caused by the mutation at the bifurcation point and put forward a chaos regulating method for human-machine-environment mine production safety system. To ensure the safety in complex system, Kletz (1978) introduced a design philosophy of intrinsic safety, i.e., a system's intrinsic safety requires basic interaction, standard interaction and cultural interaction during the operation process. However, the existing intrinsic safety evaluation methods typically focus on a single index without the interaction and coupling among various indices. In fact, accidents are mostly caused by the combined action of multiple factors. Zio (2016), by looking at the state and structure to evaluate the safety of power systems, offered a systematic perspective which also inspired the present study: the causes of accidents are to be analyzed from two aspects, namely, the factors' own

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characteristics and the relations among them.

For a complex system, in-depth knowledge of the correlation mechanism of accident causes is crucial for system safety. However, multiple safety factors in a complex system are quite complex and often constitute multiple loops to form a three-dimensional (3D) network structure, which is not adequately analyzed using traditional linear analysis modes(Dekker et al., 2011; Leveson, 2011, 2012; Loiselle et al., 2016; Rasmussen, 1997; Zio, 2016). Various analyses on accident causes in complex systems have been explored. Dekker et al. (2011) proposed the post-Newtonian analysis; Komljenovic et al. (2016) established a high-risk information framework and validated its effectiveness via asset management. Meanwhile, methods, tools and techniques in complexity science domain, such as structural equation model (SEM), interpretative structural modeling (ISM), decision making trial and evaluation laboratory (DEMATEL), multi-agent model and network analysis are developed, as well as some complexity-related techniques such as data mining, scene modeling, dynamic system modeling, artificial intelligence and evolutionary game theory(Bukowski, 2016; Farmer, 2012; Gaha, 2012;Guo, 2012; Kremers, 2012;OECD, 2009, 2011; Rzevski and Skobelev, 2014; Wang et al., 2011; Yin et al., 2012).

A complex system always fails in a complex way, and methods to effectively address complex problems are necessary (Årstad and Aven, 2017). Among the above-mentioned methods, SEM should be established on the basis of a great number of questionnaires; ISM, which is easy to grasp and enjoys most extensive applications, takes great amounts of matrix computation resource; compared with ISM, DEMATEL contains less information, but is simpler in calculation; network analysis now is widely applied, but has a high calculation complexity. After overall consideration, this study combined DEMATEL and ISM to sort out the relations among the influencing factors of mine production safety and established a multi-level hierarchical structure model; then, the importance of the factors and hierarchical relationships among the influencing factors were determined and the influences of these factors on mine coal accidents were identified; finally, some targeted countermeasures were proposed. This study provides theoretical basis and methods to prevent coal mine accidents.

1. Analysis of the influencing factors of production safety in a coal mine

1.1. Identification of risk factors in mine production safety

The factors that affect production safety in a coal mine were first reviewed on individual level before the accident causes were identified. However, the complex system's safety is also affected by the interactions among various factors. The influencing factors of a mine production system constitute a 3D network with quite complex relations and interactions, exhibiting strong nonlinearity and back-feeding with emergent effects on the whole system. In this way, safety problems are control problems rather than choice or decision problems. Many scholars also agree with this opinion (Dekker et al., 2011; Pate-Cornell, 2012; Zio, 2016).

According to the statistics of 58 death accidents in different coal mines in Shandong, China, from 2010 to 2014, which involve roof, transportation, machine and electricity, gas, blasting, water disaster and ventilation, they are the results of the interactions multiple factors including miners, machines, environment and management rather than a single cause in each case. The interactions made the system uncertain and overall opaque, reducing human's capability and aggravate the misoperation-induced consequences(Årstad and Aven, 2017; Aven, 2014; Dekker et al., 2011; IAEA, 2013; Leveson, 2011, 2012; Loiselle et al., 2016; Marais et al., 2006); when the system reaches the safe state threshold, accidents spring out. In its human error control study, DoE (2009) proposed the thought that accidents result from the poor system operating state (i.e., problems occur in the network) which is beyond the system safety standard. Accordingly, the system was divided into organizational factors, workplace condition, individual behavior and consequence, among which the importance of organizational factors was stressed. Zwetsloot et al. (2017) investigated the accidents in 27 European companies and concluded that organizational management, safety culture and employee participation were significant for accident prevention. When implementing control theory-based complex system safety control, the following factors are usually considered: human factors, organizational factors, management factors and physical system (Wang et al., 2015). In this study we summarize the coal mine accidents causes from four aspects (specifically, human, machine, environment and management), and divided the influencing factors into six categories: organizational management, squad leaders, front-line workers, safety culture, machines & equipment and operating environment.

1.1.1. Organizational management factors

Komljenovic et al. (2017) analyzed the accident prevention measures in mining industry and pointed out that organizational risk was more important and organizational performance should be attached much importance. Reason (2006) found that organization errors appeared in the accidents repeatedly. Loiselle et al. (2016) stated that organizational weakness should be explored to analyze profound factors of accidents. These results fully demonstrated the importance of organizational management factors in system accident prevention. Therefore, in analyzing the accident causes, the organizational risks should be fully explored and more effective measures taken to enhance the organizational management performance. While the effectiveness of traditional top-down management of complex systems is being questioned(Stacey and Mowles, 2016; Uhl-Bien et al., 2007; Verma and Chaudhari, 2016; Wahlstrm, 2011), for higher management efficiency Dekker and Pruchnicki (2014)proposed to manage the deviation from operation safety procedures and design standard for gradual standardization and rationalization. The monitoring system should be reinforced to acquire solid evidence, and safety-related important factors be identified and predicted for more specific standards and more strict control (Dekker and Pruchnicki, 2014; Hollnagel, 2014). The premise of mine production safety is to formulate feasible operating plan, of which the rationality sources from effective communication. By analyzing previous research results, we selected operating plan, safety investment level, rules & regulations, safety supervision and communication as the indices for organizational management.

1.1.2. Human factors

Human errors are significant accident risks. Lin and Xu (1996) conducted the related research and concluded that over 88.3% of mine accidents in China are induced by human factors. Jia (2015) pointed out that human factors account for 91.38% of the total coal mine accidents. However, traditional linear risk model is insufficient to deal with human errors (DoE, 2009; IAEA, 2013; Loiselle et al., 2016; Mosey, 2014; Zio, 2016). In this study complexity theory is employed to analyze human factors from two dimensions: squad leaders and front-line workers.

Squad leaders are the bellwethers in team production safety, whose safety consciousness affects not only the balance between safety and productivity but also the front-line workers' behaviors. Squad leaders are also the communication media between management and front-line workers, whose leadership and coordination abilities also directly affect the team cohesiveness, safety climate and interpersonal relationship in the sub unit. The squad leaders' influence is comprehensively considered from two perspectives: safety consciousness and leadership & coordination ability.

Front-line workers in China's coal mining industry differ significantly in quality and habits. Cognitive errors, rule-based errors and skill errors by Rasmussen (1997) did well in error analysis of front-line workers. The front-line workers factors are comprehensively considered from five aspects: individual characteristics, work satisfaction, safety awareness, knowledge & skills and adaptability.