An Underground Mine Risk Identification Model and Safety Management Method Based on Explanation Graph-Probabilistic Multi-Plan Analysis (EG-PMPA)

RUGAO GAO$^{1,2,3}$ (Member, IEEE), KEPING ZHOU$^{1,3}$, CHUN YANG$^{1,3}$, AND KE ZHU$^1$

$^1$School of Resources and Safety Engineering, Central South University, Changsha 410083, China
$^2$Department of Mining and Materials Engineering, McGill University, Montreal, QC H3A 2A7, Canada
$^3$Research Center for Mining Engineering and Technology in Cold Regions, Central South University, Changsha 410083, China

Corresponding author: Chun Yang (chunyang@csu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Project 51774323, and in part by the Fundamental Research Funds for the Central Universities of Central South University, China, under Grant 2018zzts216.

ABSTRACT In view of the problems of an imprecise safety system and the inefficient implementation of responsibility in current underground mining, this study reveals the internal relationship of underground mining safety management on the theoretical basis of process node management and probabilistic multi-plan analysis (PMPA). By introducing a probabilistic multi-planning identification accident analysis algorithm, a behavioural event planning library and a basic event explanation graph (EG) are constructed to determine all possible behavioural explanation sets of the top event plan/goal. By defining the importance of the explanation sets, the importance of the explanation set paths is sorted, and the important explanation set achieved by the top event goal is found. Based on the validation, the EG accident analysis model proposed in this paper is used to quantitatively analyse and rank the key risk factors in the modelling calculation of the risk control case of stope blasting operations and to propose a risk factor management control implementation plan, further verifying the feasibility of applying the explanation graph-probabilistic multi-plan analysis (EG-PMPA) framework model in underground mining safety systems.

INDEX TERMS EG-PMPA, key risk factor, mining safety management, process node.

I. INTRODUCTION

In the construction of the national economy, mining is an important raw material industry that provides a large amount of primary energy, industrial raw materials and agricultural means of production for economic development and daily life [1]. Restricted by the overall slowdown of global economic growth, the demand for mineral resources in China and other developing countries is still at a high level in the long run, and the mining industry will develop in a continuous and stable manner over a long period of time [2], [3]. However, the mining industry must be fully aware that the situation of mining safety is still rather serious. Take China as an example: the underground mining production system of major resource development enterprises is large and complex, and there are numerous potential hazards in the production process. At present, underground mining accidents still occur frequently, causing many casualties and much loss of property. Underground mining accidents usually take place abruptly, with a wide range of influences and serious consequences [4], [5]. Underground mining is an accident-prone area, the safety of which has always been the focus of safety management. According to figures released by the National Bureau of Statistics on February 28, 2020, a total of 29,519 people died in various production safety accidents in 2019. There were 100,000 employees in industrial, mining and commercial enterprises, among whom 1.474% died in production safety accidents, a decrease of 4.7% over the previous year, and 0.083% died in coal mines for every million tons, a decrease of 10.8% [6]. Although the
death toll has been declining in recent years, accidents still frequently occur [7]. According to the analysis results of accidents involving mining deaths, production safety accidents in underground mines mainly result from improper operations by miners, unapproved materials and equipment, and deficient safety management [8], [9]. In the work of mine safety production, there are mainly problems such as incomplete safety production legal systems, incomplete safety management systems, insufficient safety investment, low safety science and technology levels, a backward safety culture, and a lack of self-disciplinary mechanisms and self-management capabilities in large enterprises. The safety status of an enterprise entirely depends on its safety management efficiency. Outdated and inappropriate safety management models will affect the production of enterprises and cause serious harm to them. Although the key problems in underground mining safety production at this stage are well known and the safety management and standardization of underground mines have been greatly improved, much work needs to be done to explore a more systematic, standardized, and scientific risk analysis and operable safety management mode.

In view of the problems faced by underground mining enterprises, namely, the bottleneck in safety management theory development, the lack of a systematic standardized process, and the deficient implementation of safety management, this study proposes an accident analysis method based on explanation graph-probabilistic multi-plan analysis (EG-PMPA) by introducing the theoretical basis of process node management and probability risk identification and combining the advantages of multi-planning identification in the multi-objective, procedural and interpretive aspects of behaviour analysis. Through the construction of a behaviour event planning library and a basic event explanation diagram, all possible behaviour explanation sets for top event planning or objectives are determined, and the degree of importance of the explanation set paths is sorted by defining the degree of importance of the explanation sets to realize the risk identification functions of process and node objects and the sequence of accidents. Combined with the identification results of the process node risk factors in the case, the EG accident analysis model is adopted to quantitatively analyse and rank the key risk factors, based on which a refined risk factor management and control scheme is constructed. The method proposed by this study can obtain a reasonable explanation of the top-level accident cause by calculating the event logic relationship and the probability of occurrence, and it can classify the basic events that require multi-objective control. By emphasizing the proceduralization of safety management and whole-process management, the method facilitates the meticulous discovery of various accident hazards and problems as well as the clear identification of the accident link. Additionally, the research results can be effectively applied in engineering practice.

II. RELATED WORK

Over the years, many researchers have devoted themselves to the research and development of theories and models of risk identification and safety management, and they have made some achievements [10]–[12]. Regarding risk identification, Yang [13] proposed a dynamic risk identification model based on integrating the immune optimization algorithm (IOA) [13]. A dedicated human and organizational factor model of ship collision accidents between an assisted ship and an icebreaker was developed by Zhang et al. [14]. Taofeeq et al. [15] employed a quantitative research design following the positivist research paradigm to determine the factors influencing contractor risk attitudes. These methods are closely related to human factors. Currently, behaviour analysis combined with human factors has been widely applied in the field of national and social public security and decision-making evaluation. Traditional methods of behaviour analysis are mainly based on Markov or Bayesian models or the direct study of human factors [16]–[19]. These kinds of methods adopt a non-hierarchical programming representation, which can infer the intention and goal of an agent from different abstract levels. However, since the objectives at different levels all need to be identified, there are deficiencies in the in-depth analysis of behaviour and the explanation of the results, greatly increasing the workload of the identification task [20], [21]. The main purpose of behaviour analysis is to identify goal-oriented planning, and a method of behavioural intention analysis based on planning knowledge can better solve the problem [22].

The idea of process management with regard to safety management combined with risk assessment was first proposed by scholars in the early 20th century. This approach includes Gantt charts, network planning technology, material requirement planning, enterprise resource planning and business process reconstruction [23]. In recent years, process management has become not only an important management means in the field of business management but also the theoretical basis for all walks of life to explore more advanced management modes [24]–[27]. Currently, researchers have proposed a variety of process management methods that can help to find the key process nodes, and such methods have been applied in some enterprises. In China, compared with the safety standardization management mode implemented by underground mining enterprises, the process management process is more rigorous and reliable, facilitating the implementation of standardization in all aspects of safety production. In the current stage, process node management has a certain theoretical basis in the field of safety, but research on and the application of the management system formed by the combination of process nodes and risk management do not frequently occur. Moreover, much of the practice of process node theory in mining enterprises is still in the framework and guidance stage. More research and practice in the field of system safety and risk assessment are needed.
I. INTRODUCTION

II. PROPOSED METHODOLOGY

A. UNDERGROUND MINING RISK IDENTIFICATION BASED ON A PROCESS NODE

Due to the differences in risk characteristics, safety production conditions, organizational settings, management levels, etc., the process node management system for different underground mining enterprises will also be different, but in general, the scope of hazard identification is similar to the range of risk assessment. Therefore, this paper takes the more common function management system, production system and operation system as the basis to make the constructed model more applicable. Moreover, combined with the basis of identifying hazardous and harmful factors in underground mines, some process nodes are endowed with risk attributes to realize safe production and operation [28]. The process can be classified based on the hierarchy of family, group, composite, base and process nodes, which is suitable for a process system with a large production system, a complex management level and special business requirements. The basic process is described in Table 1.

A cross-department process group can be constructed for an underground mining production system under complex conditions such as the safety management of the roof, the management of the shaft and the mining shaft, the management of the blasting equipment and its safety, ground pressure monitoring and prevention, the safety management of the power supply and consumption, underground ventilation and dust control management, filling management, and underground transportation management [29]. Based on the process factors, each process group can be further sub-divided into organized compound processes. In other words, the department processes (production processes) can then be divided into multiple organized basic processes, that is, operation team processes or production personnel processes. Finally, the basic processes can be broken down into process nodes, that is, the minimum risk factor identification and management unit. The process node hierarchy diagram is shown in Fig. 1.

Table 1. Description of basic process types.

| Process types       | Basic concepts                                                                 | Management level   |
|---------------------|--------------------------------------------------------------------------------|--------------------|
| Process family      | A process that considers the whole process of underground mining enterprise strategy and the operation level | Enterprise         |
| Process group       | A unit-level process with different production or management functions in underground mining operations | Department         |
| Compound process    | A class of processes with clear position and function attributes or nested base processes in the next level of a functional unit | Group/Process      |
| Basic process       | Two or more process nodes are organically combined to realize a specific value output through effective organization | Group               |
| Process node        | The unit of the basic process; it has clear executive positions and responsibilities and is the minimum control unit for attribute analysis and the whole-process business function | Operation          |

In the cross-functional process chart, process nodes at different levels can be divided into the start node, interface node, process node, judgement node and end node based on the needs of process operations and the role of process nodes in the process. The definitions and characteristics of each type are shown in Fig. 2.

Safety principles are highly applicable and interdisciplinary. However, practical applications have shown that only if process management is combined with safety or risk management (i.e., the use of the process node model to achieve effective risk prevention and control) will safety management be effectively implemented. The principle of safety control based on the process node can be summarized as follows: (1) the realization of safety management based on function process construction; (2) the realization of safety control based on the property of the process node; (3) the realization of risk control based on the identification of key processes; and (4) a linkage mechanism for multi-level and multi-cycle effects. The operational relationship is shown in Fig. 3.
The models of processes at different management levels, such as composite processes, basic processes and process nodes, can be constructed by a cross-functional process chart. Each process level generally includes four basic process elements, namely, the start, processing, judgement and end. The general process node and judgement node feature four attributes, namely, basic, composition, function and value attributes. The basic properties of the process nodes are shown in Table 2.

Based on the different functional requirements of process operations, the functional attributes of process nodes can be further developed at different levels. The risk attribute is a key point of the process security control principle as well as an important combination point of risk analysis and evaluation in the process [30]. By combining the concept of process management and the classification of dangerous and harmful factors in site safety management, the node risk attributes are classified as position, resource, environmental and internal risks [31]. The concept of process management and refinement is embodied in the process of risk factor identification and classification. Considering the requirements of process node management in this study, the framework of relationships in underground mining safety process management is established, as shown in Fig. 4.

**B. EXPLANATION GRAPH THEORY OF PROBABILISTIC PROGRAMMING**

The planning identification method shows great advantages in predicting whether human or organizational behaviours are involved. Traditional organizational planning usually assumes that intelligent agents such as humans or organizations carry out only a single plan each time. However, in a complex actual environment, the behaviour of individuals or organizations is changeable, and it is likely that they...
The planning library is a collection of hierarchical partial-order plans. The basic behaviour in the planning structure corresponds to AND node “∧” or OR node “∨”. At the AND node, each child node is decomposed from the parent node with the reunification probability, while at the OR node, the sum of the reunification probabilities of all child nodes equals 1. Then, an EG is constructed based on the given planning library, as shown in Fig. 7, which is a directed weighted graph. Each node in the graph represents a concrete or abstract behaviour. The edges and directions between nodes represent decomposition or materialization relationships, and the probability on the edges represents the decomposition probability or materialization probability. The constructed graph is called the EG of observation quantity O, which contains all possible explanations corresponding to the observed behaviour.

After the planning library is given, the observation set is assumed to be \( O_{1:i} = \{O_1, CO_2, C \cdot \ldots \cdot CO_n\} \), and the probabilistic computing of explanations is \( E_j \). Thus, the conditional probability calculation formula is as follows [37]:

\[
P(E_j | O_{1:i}) = P(O_{1:i} | E_j) P(E_j) / P(O_{1:i})
\]

1/P \( (O_{1:i}) \) is a constant for each EG, and \( P(O_{1:i} | E_j) \) is the occurrence probability of \( O_{1:i} \) when \( E_j \) is given an explanation the value of which is fixed to 1. \( P(E_j) \) is the prior probability, that is, the original probability of EG in the tree structure.

Assuming that the top goal is \( G_{1:m} = \{G_1, G_2, \ldots, G_m\} \) and the sub-goal is \( SG_{1:m} = \{SG_1, SG_2, \ldots, SG_n\} \), the node set of \( E_j \) can be defined as \( V = \text{dummy} \cup G_{1:m} \cup SG_{1:n} \cup O_{1:i} \). \( E = \{e_1 = \text{dummy} \rightarrow G_1, CG_2, C \cdot \ldots \cdot Ce_{e_j} = SG_{1} \rightarrow SG_y, C \cdot \ldots \cdot Ce_{e_j} = SG_{2} \rightarrow O_{1}\} \) is the edge set of \( E_j \), and \( 1 \leq x, Cy, Cz \leq n, C1 \leq s \leq t \). Assuming that the decomposition of each behaviour is directly affected by the parent node,
The prior probability of explanation $E_j$ is as follows:

$$P(E_j) = P(V, E)$$

$$= P(O_1, C_{e_1} | V/O_1, CE/e_1) \cdot P(iV/O_1, CE/e_i)$$

$$= P_{e_1} \cdot P(V/O_1, CE/e_i)$$

$$= P(\text{dummy}) \cdot \prod_{\text{edge} \in E} P(\text{edge})$$

In the formula, given $(V/O_1, CE/e_i)$, $P(O_1, C_{e_1} | V/O_1, CE/e_i)$ is the probability after breaking down the rule, $e_i$. Based on the decomposition hypothesis, $P(O_1, C_{e_1} | V/O_1, CE/e_i) = P(e_i = SGZ \rightarrow O_1)$. $P(\text{edge})$ is the a priori probability of the middle edge, and $P(\text{dummy})$ is the a priori probability of organizational goal pursuit, which is constant for every explanation.
The method of finding the optimal explanation can be expressed as follows:

$$E_{\text{max}} = \arg \max_{E_j \in E} P(O_{1:1} | E_j) P(E_j) / P(O_{1:1})$$

$$= \arg \max_{E_j \in E} \prod_{\text{edge}_{i} \in E_j} P(\text{edge}_{i})$$

$$= \arg \max_{E_j \in E} \sum_{\text{edge}_{i} \in E_j} \ln(P(\text{edge}_{i}))$$

$$= \arg \min_{E_j \in E} \sum_{\text{edge}_{i} \in E_j} \ln(P(1/\text{edge}_{i})) \quad (3)$$

In the formula, $P(\text{edge}_{i})$ is the decomposition probability connected by $\text{edge}_{i}$. Defining $\ln(P(1/\text{edge}_{i}))$ as the weight of $\text{edge}_{i}$, since $0 < P(\text{edge}_{i}) < 1$, we can conclude that $\ln(P(1/\text{edge}_{i})) > 0$.

$\ln(1/P(e))$ is weighted for each line of the EG, and $P(e)$ is the probability of line $e$. Then, the whole EG is transformed into a weighted digraph. The issue of finding the best explanation is redefined as finding the minimum weight tree in the EG. The fixed point of the tree is the “dummy” node, and the leaf node is the observation quantity.

**IV. CASE STUDY**

The previous theoretical derivation suggests that probabilistic programming identification is feasible for accident behaviour analysis. Taking an underground mine electric locomotive
collision accident as an example, the construction steps and demonstration process of the accident analysis model are illustrated.

**A. EG-BASED PROBABILISTIC PROGRAMMING ACCIDENT ANALYSIS MODEL**

First, accident behaviour should be identified; that is, all relevant accident behaviours that may lead to top accidents should be identified. Then, an accident behaviour planning database should be established, as shown in Fig. 8. The nine partial-order plans in the figure include all the basic behaviours (or states) that lead to top accidents. To prevent the occurrence of top accidents, it is necessary to prevent the realization of $G_1$ and $G_2$. Observation behaviour set $O$ is defined as $O = \{A_1, A_2, A_3, \ldots, A_{14}\}$. In the planning structure, $G_1$, $G_2$ and SG6 correspond to AND nodes, and the probability of the edge between each node is the materialization probability of each basic event or sub-goal. SG1, SG2, SG3, SG4, SG5 and SG7 correspond to OR nodes of the planning structure. If the behaviour is observed at the SG1 node, it may execute “sleep on the track” with a certain probability, “rush to the road with the locomotive”, “illegal proposal”, or “slip of the locomotive”. The probability sum of the four observations is supposed to be one.

The EG is constructed based on the given behaviour observation set $O$ and PL. For each behaviour observation $A_i$ ($i = 1, 2, 3, \ldots, 14$), $A_1$ is first added to the EG. There is a search for the behaviour in the behaviour planning library to find its parent node and add it to the EG. The structural relationship at the node should be consistent with the planning library.
Then, other observation behaviours are added in turn, and its parent node is expanded in the same way until all observation behaviours are expanded. Repeated nodes in the expansion process are merged until no new nodes are added. Finally, vertex G is added to the top of the EG to connect to the two goals $G_1$ and $G_2$; thus, the construction of the EG is completed, as shown in Fig. 9. The EG contains all possible explanation paths corresponding to the behavioural observations. Signs such as $e_1$, $e_2$, . . . , and $e_{20}$ are the numbers connecting the edges of each adjacent node.

The best explanation path leading to the top goal can be found through the EG. Equation (3) shows that each edge in the EG needs to be weighted by $\ln(1/P(e))$. Based on the statistics of the accident probability data, the probabilities of event occurrence corresponding to the behaviour observation quantities $A_1, A_2, A_3, . . . , A_{14}$ are shown in Table 3 [38].

Based on Table 3, the materialization probability $P_1, P_2, . . . , P_{20}$ of each node edge in the EG can be calculated. At the AND node, the probability of each connecting edge is its materialization probability. At the OR node, the materialization probability of each edge is first calculated, and then, the sum of the probability of each connecting edge equals 1 through normalization processing. For nodes that mix AND and OR (such as the $SG_3$ node), normalization is carried out on the basis of satisfying the logical calculation relationship, such as the logical relationship of the $SG_3$ node: $P_{14} + P_{15} + P_{16} \times P_{17} = 1$. The decomposition probability of each edge is determined.

Based on the above rules, the probability of each directed edge in the EG, $P(e_i)$, and the weight value of the corresponding edge, $w_i$, can be calculated. $w_i = \ln(1/P(e_i))$, and the results are shown in Table 4.

The value of $w_i$ represents the magnitude of the value, indicating the importance of the occurrence probability of the child node (basic behaviour or sub-goal) connected to the directed edge to the occurrence probability of the parent node.
(sub-goal or top goal). The greater the value of \(w_i\), the less important the corresponding child node is to the parent node, and vice versa.

The EG is a tree structure with 21 nodes, 20 edges, 14 behaviour observations, 4 sub-goals and 2 top goals to be controlled. Concerning the tree-structured EG, the total number of \(SE_i\) in the explanation set is the total number of basic behaviour observations. The corresponding explanation sets of behaviour observations \(A_1, A_2, A_3, \ldots, A_{14}\) are as follows:

\[
\begin{align*}
SE_1 &= \{G_1, A_1SE_2\} = \{G_1, SG_1, A_2\} \\
SE_3 &= \{G_1, SG_1, A_3SE_4\} = \{G_1, SG_1, A_4\} \\
SE_5 &= \{G_1, SG_1, A_5SE_6\} = \{G_2, SG_2, A_6\} \\
SE_7 &= \{G_2, SG_2, A_7SE_8\} = \{G_2, SG_3, A_8\} \\
SE_9 &= \{G_2, SG_3, A_9SE_{10}\} = \{G_2, SG_3, A_{10}\} \\
SE_{11} &= \{G_2, SG_3, A_{11}SE_{12}\} = \{G_2, SG_4, A_{12}\} \\
SE_{13} &= \{G_2, SG_4, A_{13}SE_{14}\} = \{G_2, SG_4, A_{14}\}
\end{align*}
\]

The explanation set is a behaviour sequence from top goal \(G_1\) or \(G_2\) to behaviour observation \(A_i\), representing the realization path of top events when basic events occur. It is also an accident chain cutting path for accident prevention and control. Since each basic behaviour in this paper corresponds to only one goal or sub-goal, the form of the explanation set is relatively simple. If the behaviour observation quantity corresponds to multiple goals or sub-goals at the same time, the calculation and expression methods of the explanation set are similar. To define the importance of the explanation set, which represents the importance of the explanation set to the top objectives, the calculation formula is as follows:

\[
W(SE_i) = \sum_{edge, j \in E_j} w_i
\]

(4)

In the formula, \(W(SE_i)\) is the magnitude of the explanation sets; \(w_i\) is the weight value of each directed edge of the explanation path of observation \(A_i\).

The value of \(W(SE_j)\) itself has no specific meaning to the EG, but its value can directly represent the influence of the basic behaviour observation quantity on the top goal in the explanation path to find the optimal explanation set of observation behaviours in the EG. The smaller the value of \(W(SE_i)\) is, the greater the influence of the basic observation quantity \(A_i\) on the top goal, which is supposed to be highly controlled, and vice versa. According to equation (4), the magnitude of explanation sets \(SE_1, SE_2, \ldots, SE_{14}\) is calculated and sorted based on the value, as shown below:

\[
\begin{align*}
W(SE_1) &= 0.73233 & W(SE_2) &= 3.69579 \\
W(SE_3) &= 2.62129 & W(SE_4) &= 3.00279 \\
W(SE_5) &= 1.64809 & W(SE_6) &= 9.5711 \\
W(SE_7) &= 9.5711 & W(SE_8) &= 9.5722 \\
W(SE_9) &= 9.5722 & W(SE_{10}) &= 10.9996 \\
W(SE_{11}) &= 10.3065 & W(SE_{12}) &= 9.5962 \\
W(SE_{13}) &= 9.5962 & W(SE_{14}) &= 8.5217
\end{align*}
\]

The smaller the value of \(W(SE_i)\) is, the greater the magnitude of the explanation set to the top objectives, the calculation formula is as follows:

\[
W(SE_1) < W(SE_5) < W(SE_3) < W(SE_4) < W(SE_2) < W(SE_{14}) < W(SE_6) = W(SE_7) = W(SE_8) = W(SE_9) < W(SE_{12}) = W(SE_3) < W(SE_{11}) < W(SE_{10})
\]

The distribution table of the magnitude values of the explanation sets is shown in Table 5. The smaller the value is, the greater the magnitude, and the greater the possibility of an accident. Consequently, the basic event behaviour within the small value interval should be proactively prevented and controlled.

**B. DEMONSTRATION OF THE RELIABILITY OF THE MODEL**

FAT analysis is a common method in accident safety assessment. In the quantitative analysis of FAT, the critical importance coefficient is often used. This coefficient refers to the ratio of the relative change rate of the occurrence probability of a basic event to the change rate of the occurrence probability of the top event, also known as the “risk importance factor” [39], [40]. FAT analysis is used to quantitatively analyse the accident of the underground electric locomotive colliding with people, and its probability of a top event of the “AND gate” is as follows:

\[
P = \prod_{i=1}^{n} q_i
\]

(5)

The probability of the top event of the “OR gate” is as follows:

\[
P = 1 - \prod_{i=1}^{n} (1 - q_i)
\]

(6)

\(q_i\) is the occurrence probability of the \(i^{th}\) basic event.

The minimum cut set method is used to calculate the probability of the top event, and it can be expressed as follows:

\[
Q = \sum_{j=1}^{k} \prod_{i \in k_j} q_i - \sum_{1 \leq s \leq k} \prod_{i \in k_j} q_i + \ldots + (-1)^{k-1} \prod_{j=1}^{k} q_{i} \quad x_i \in k_j
\]

(7)

In the formula, \(i\) is the ordinal number of the basic event; \(x_i \in k_j\) is the \(j^{th}\) of the basic event belonging to the \(j^{th}\) minimum cut set; \(k\) and \(s\) are the ordinal numbers of the minimum cut set; \(k\) is the number of the minimum cut set; \(x_i \in k_j \cup k_s\) is the \(j^{th}\) basic event \(x_i\) belonging to the \(j^{th}\) minimum cut set; and \(1 \leq j \leq s \leq k\) is the value range of \(j\) and \(s\).

The probability importance of basic events is expressed by the probability importance coefficient. In general, it is easier to reduce the probability of basic events with a high probability than to reduce the probability of basic events with a low probability. However, the probability importance coefficient fails to reflect this fact. Therefore, it is necessary to adopt the ratio of the relative change rate to measure the importance of each basic event, that is, the ratio of the change rate of the occurrence probability of the basic event to that of
the top event, to determine the importance of each basic event, known as the critical importance coefficient:

\[ I_e(i) = \frac{\partial \ln Q}{\partial \ln q_i} \quad \text{or} \quad I_e(i) = \frac{q_i}{Q} f(P(i)) \quad (8) \]

The critical importance of the event is calculated as follows:

- \( I_e(1) = 0.854 \)
- \( I_e(2) = 0.073 \)
- \( I_e(3) = 0.213 \)
- \( I_e(4) = 0.145 \)
- \( I_e(5) = 0.563 \)
- \( I_e(6) = I_e(7) = 0.003 \)
- \( I_e(8) = I_e(9) = I_e(10) = I_e(11) = 0.001 \)
- \( I_e(12) = I_e(13) = 0.0012 \)
- \( I_e(14) = 0.035 \)

Therefore, the order of critical importance is as follows:

\[ I_e(1) > I_e(5) > I_e(3) > I_e(4) > I_e(2) > I_e(14) > I_e(6) \]
\[ = I_e(7) > I_e(12) = I_e(13) > I_e(8) = I_e(9) \]
\[ = I_e(10) = I_e(11) \]

By comparing the weight value ranking and critical importance coefficient ranking of the explanation set, the calculation results of the two methods are found to be basically the same. However, there is no particularity or pertinence in the selection of planning library events and the selection of basic event probability values in this study. Consequently, the importance ranking of the explanation set obtained by the EG algorithm is credible, and it is feasible to apply the EG algorithm based on multi-programming recognition of accident behaviour analysis.

Compared with probability importance coefficient \( I_e(i) \), the importance of the explanation set \( W(SE_i) \) obtained via the EG algorithm has obvious advantages, effectively dealing with situations in which the probability importance coefficients of several basic events are equal. The number of basic events selected in this paper is relatively small, the planning library and EG structure are relatively simple, and there are a few cases in which the ranking of the importance of the explanation set cannot be conducted. For example, the occurrence probabilities of basic events \( A_9 \) and \( A_7 \) are both 0.028, and the directed logical relationship of the two events to the top goal consists of passing through the OR node and then the AND node at the same time. In addition, compared to the quantitative analysis method of FAT, the results of the EG algorithm focus more on the path of the accident, that is, the sequence of accident behaviours, to clearly locate the cause section in the accident cause chain. The advantage of the EG algorithm is particularly obvious for situations in which a certain behaviour observation (or sub-goal) achieves multiple sub-goals (or goals) at the same time. The best explanation path can be found to determine which path of the behaviour observation (or sub-goal) has a greater impact on the sub-goals (or goals) and must thus be strictly controlled.

By sorting and demonstrating the importance of the explanation set, the following results are obtained:

1) Explanation set \( SE_1 \) is the most important to the top events, and basic event \( A_1 \) on this explanation path should be given the greatest attention, followed by \( A_5 \), \( A_3 \), \( A_4 \), . . ., while \( SE_{11} \), \( SE_{10} \), etc. are less important to the top events, and their corresponding basic events and paths can be placed in a secondary position.

2) The value of \( W(SE_i) \) suggests that the importance value of each explanation set on the branch of top goal \( G_1 \) is significantly less than that of each explanation set on the branch of top goal \( G_2 \), and there are obvious intervals. Therefore, in accident prevention and control, more attention should be paid to the basic events on the branch road where \( G_1 \) is located.

3) To prevent the realization of top goal \( G \), that is, to effectively control the occurrence of human accidents in underground electric locomotive collision accidents, it is necessary to prevent the realization of \( G_1 \) and \( G_2 \) at the same time. Therefore, the basic events on the path of these two objectives can be classified in a simple manner so that accident prevention can be focused on. More attention should be paid to controlling the basic events with smaller structure importance values on the two branches, such as \( A_1 \), \( A_5 \), and \( A_3 \) on the \( G_1 \) branch and \( A_{14} \), \( A_6 \), and \( A_7 \) on the \( G_2 \) branch.

The EG calculation method based on probabilistic multi-programming theory is based on the hierarchical programming library and observation set. The algorithm starts from the observation quantity and extends the EG from bottom to top until vertex \( G \) is expanded. The explanation set and the importance of the explanation set of all behaviour observations are obtained by calculation. For accident behaviour analysis with a large number of basic events, the complex

| Intervals       | [0,1] | [1,5] | [5,10] | [10,∞] |
|-----------------|-------|-------|--------|--------|
| Explanation sets | \{G_1, A_1\} | \{G_1, SG_1, A_3\} | \{G_2, SG_4, A_{14}\} | \{G_2, SG_3, A_{11}\} |
|                 | \{G_1, SG_1, A_3\} | \{G_2, SG_2, A_6\} | \{G_2, SG_2, A_7\} | \{G_2, SG_3, A_{10}\} |
|                 | \{G_1, SG_1, A_4\} | \{G_2, SG_3, A_8\} | \{G_2, SG_1, A_9\} | \{G_2, SG_4, A_{12}\} |
|                 | \{G_1, SG_1, A_2\} | \{G_2, SG_4, A_{13}\} | \{G_2, SG_4, A_{11}\} | \{G_2, SG_4, A_{13}\} |
logical structure of behaviour planning and the heavy workload of EG construction, especially the analysis of complex actors with multiple behaviour observations (or sub-objectives) corresponding to multiple sub-objectives (or objectives), can be solved layer by layer, refined safety management.

C. APPLICATION OF NODE RISK MANAGEMENT AND CONTROL BASED ON THE EG-PMPA MODEL

Compared with traditional risk analysis methods such as event tree analysis, operation condition analysis and fish bone diagrams, the accident analysis model of behaviour planning identification shows obvious advantages in multi-objective and process explanations of risk identification [41]. The blasting operation process was selected as the research object, the process node diagram was constructed, and qualitative description of the node risk attribute was performed. The process node factors were quantitatively sorted by using the behaviour planning identification method, and the key risk factors were identified. Finally, the risk control mode of the blasting operation process was constructed. The construction of the blasting work process adopts the operation flow and node diagram. First, detailed operation activity analysis is conducted, and the main type of worker in blasting

| Types of risk | Risk factors | Risk factor analysis table of blind shot inspection and analysis. |
|---------------|--------------|-------------------------------------------------------------------|
| Position Risk | Design of the position process | P1 Improper analysis of the blind shot inspection process and key points |
| Resources Risk | Resource usage risk | P2 Failure of detonating network techniques |
| Environmental Risk | Environmental design risk | P3 Improper operation of detonation |
| | Environmental input risk | P4 Incorrect operation of detonation |
| | State change risk | P5 Failure to check the detonation network connection |
| | Environmental output risk | Failure to conduct the wire continuity inspection |
| | Institutional risk | R1 Failure of the detonating conductor |
| | Design verification risk | R2 Failure of the bridge wire of the detonator |
| | Mission planning risk | Insufficient detonation energy |
| | I1 Unreasonable charge structure such as clearance |
| | I2 | Damp explosives due to improper storage |
| | I3 | Damp detonating charge due to long-term storage |

| Name of process: Blasting operation |
| Name/No. of node: inspection and analysis of blind shots D20 |
| Types of risk | Type of node: Interface node | Functions of node positions: Group leader |
|---------------|----------------|------------------------------------------------|
| Design of the position process | P1 Improper analysis of the blind shot inspection process and key points |
| Design of the position process | P2 Failure of detonating network techniques |
| Technical input position education factors | P3 Improper operation of detonation |
| Position status factors | P4 Incorrect operation of detonation |
| Resource input risk | P5 Failure to check the detonation network connection |
| Resource performance risk | Failure to conduct the wire continuity inspection |
| Resource usage risk | R1 Failure of the detonating conductor |
| Resource output risk | R2 Failure of the bridge wire of the detonator |
| Environmental design risk | Insufficient detonation energy |
| Environmental input risk | Insufficient detonation current |
| State change risk | Incorrect position of the detonating charge |
| Environmental output risk | Damp explosives without waterproof treatment |
| Institutional risk | Damp detonating charge due to improper storage |
| Design verification risk | Unreasonable charge structure such as clearance |
| Mission planning risk | Damp detonating charge due to long-term storage |
| I1 Unreasonable charge structure such as clearance |
| I2 | Damp explosives due to long-term storage |
| I3 | — |
| I4 | — |
| I5 | — |
| I6 | — |
| I7 | — |
TABLE 7. Probability and weight value of each edge of the EG.

| No. | Risk factors | Probability $P_i$ |
|-----|--------------|------------------|
| $A_1$ | Detonating network connection not checked | $2 \times 10^{-4}$ |
| $A_2$ | Technical problems with the detonating network connection | $5 \times 10^{-5}$ |
| $A_3$ | Detonating wire not checked | $5 \times 10^{-6}$ |
| $A_4$ | Quality problems with the detonating wire | $5 \times 10^{-2}$ |
| $A_5$ | Failure of the bridge wire of the detonator | $1 \times 10^{-4}$ |
| $A_6$ | Insufficient detonating current | $5 \times 10^{-6}$ |
| $A_7$ | Incorrect position of the detonating charge | $5 \times 10^{-3}$ |
| $A_8$ | Damp detonating charge due to long-term storage | $1 \times 10^{-5}$ |

TABLE 8. Weight value of the risk factors of the EG.

| No. of edges | Weight value of edges $w_i$ |
|--------------|-----------------------------|
| $c_1$ | 0.11648 |
| $c_2$ | 6.283299 |
| $c_3$ | 2.23608 |
| $c_4$ | 6.828385 |
| $c_5$ | 8.99135 |
| $c_6$ | 8.51719 |
| $c_7$ | 9.90349 |
| $c_8$ | 0.09549 |
| $c_9$ | 2.39808 |
| $c_{10}$ | 0.04879 |

| No. of edges | Weight value of edges $w_i$ |
|--------------|-----------------------------|
| $c_{11}$ | 3.04452 |
| $c_{12}$ | 0.183987 |
| $c_{13}$ | 6.39859 |
| $c_{14}$ | 1.79342 |
| $c_{15}$ | 4.11087 |
| $c_{16}$ | 0.19885 |
| $c_{17}$ | 1.80829 |
| $c_{18}$ | 0.33647 |
| $c_{19}$ | 1.94591 |
| $c_{20}$ | 1.94591 |

operations is determined to be the blasting technician, who is taken as the main construction object of the flow chart. Other types of workers include the project leader, blasting design reviewer, the blasting team leader, the rock driller and the safety inspector. Based on the main operation activities of blasting technicians and participants, a node diagram of the blasting operation process can be drawn, as shown in Fig. 10.

The node diagram includes 33 process nodes, 4 types of nodes, 15 major nodes, and 12 interface nodes, and it involves 6 functional positions. Each process node in the base process has its own number and function. The process node diagram is the basis of qualitative and quantitative risk analysis in the follow-up.

It is true that it is important to recognize blind shots and to deal with them properly. However, it is also necessary to analyze their causes so that corresponding measures can be taken to reduce the probability of similar accidents. Combining the definition of the risk attribute description of the process node mentioned above, the risk factor identification process of the node “inspection and analysis of blind shots D20” is selected here, as shown in Table 6.

The identification of risk factors in the table shows that the main causes of blind shots are “position risk” and “resource risk”, that is, the technical skills and operation status of the staff, as well as the risk of the blasting explosive device itself and the usage risk. Based on the qualitative analysis in Table 6, the following measures to avoid blind shots can be taken.

1) Strengthen the education and training of designers and constructors, and strictly comply with the design and construction specifications;

2) Strictly control the quality and inspection of blasting materials, and prohibit unapproved products from entering the warehouse or operation site;

3) Use new wires in the electric blasting network as far as possible to ensure that the detonator has sufficient electric energy. The same blasting network must adopt electric detonators from the same factory, from the same batch and of the same model;

4) Fully clean sundries around the blasthole before charging to prevent blasthole blocking or grain isolation;

5) Ensure that the charging force is appropriate, and strictly follow the designed charge density;

6) Ensure the appropriate tightness of the network connection. If it is too tight, it is easy to break, which will lead to detonation failure.
FIGURE 10. Node diagram for the blasting work flow.
Apparently, the safety precautions obtained through a qualitative description of risk are too general and intuitive, which is the case in the traditional safety management process.

In the implementation of safety standardization, the effectiveness of safety precautions should be judged scientifically. Therefore, the risk factors in the sub-process set of the node “inspection and analysis of blind shots D20” should be quantitatively described. Taking the sub-process set of the node “inspection and analysis of blind shots D20” {whether the initiation network is in good condition, whether the detonator is in good condition, whether the detonating charge is effective, whether the explosive is effective, whether the charge structure is reasonable} as the goal behaviour of the EG, the behaviour planning library is constructed, as shown in Fig. 11.

Then, it is transformed into the EG, as shown in Fig. 12. Table 7 shows the corresponding probability statistics of the event occurrence corresponding to behavioural risk factors $A_1, A_2, A_3, \ldots, A_{15}$.

Based on the calculation rules of different node types of the EG, the weight value $w_i$ of each directional edge in the EG is calculated, as shown in Table 8.

The following is the corresponding explanation set $SE_i$ of behaviour observations $A_1, A_2, A_3, \ldots, A_{15}$:

$SE_1=\{G_1, A_1\}$ $SE_2=\{G_1, A_2\}$ $SE_3=\{G_1, A_3\}$ $SE_4=\{G_1, A_4\}$ $SE_5=\{G_2, A_5\}$ $SE_6=\{G_2, A_6\}$ $SE_7=\{G_3, A_7\}$ $SE_8=\{G_3, A_8\}$ $SE_9=\{G_3, A_9\}$ $SE_{10}=\{G_4, A_{10}\}$ $SE_{11}=\{G_4, A_{11}\}$ $SE_{12}=\{G_4, A_{12}\}$ $SE_{13}=\{G_5, A_{13}\}$ $SE_{14}=\{G_5, A_{14}\}$ $SE_{15}=\{G_5, A_{15}\}$
Based on equation (4), the importance of the explanation sets $SE_1, SE_2, \ldots, SE_{15}$ is calculated and sorted based on the value, and the order is as follows:

$$W(SE_3) < W(SE_7) < W(SE_4) < W(SE_9) < W(SE_5) < W(SE_{11}) < W(SE_1) = W(SE_8) < W(SE_{12}) < W(SE_6) < W(SE_{13}) < W(SE_2) < W(SE_{10}) = W(SE_{14}) = W(SE_{15})$$

Based on the definition of the importance of the explanation set, the smaller the value of the importance of the explanation set is, the greater the importance of the explanation path to the top behaviour. That is, the order of importance of the explanation path can be expressed as in Table 9.

Based on the order of the importance value of the explanation set, the key risk factors leading to blind shots and their ranking can be determined, as shown in Table 10.

Based on the results of the risk factor identification and the key node identification of the node “inspection and analysis”
Risk factor identification and quantitative sequencing are conducted in the “blind shot operation” process. In the whole blasting operation process, the operation process node contains 15 main process nodes, and each node has several risk factors and key risk factors to form the controlling object system of the key risk factors in the whole flow chart and to conduct management based on the corresponding person responsible for each risk factor.

In summary, to refine site safety, first, “top-down” process decomposition and function division should be conducted. That is, the object of refined implementation is the risk factors of blind shots” in blasting operations as well as the basic theory of site management refinement, the daily safety control project is refined, and the person responsible for each functional position takes risk clearing measures based on the key risks of the project. The detailed implementation table of blind shot risk control is shown in Table 11. Risk clearing measures must rely on strict rules and regulations.

### Table 11. Detailed implementation table of blind shot risk control.

| No. | Name of process: Blasting operation | Name/No. of node: Inspection and analysis of blind shots D20 | Type of node: Interface node Executive control | Position of node: Group leader Executive staff |
|-----|-----------------------------------|----------------------------------------------------------|-----------------------------------------------|---------------------------------------------|
| 1   | Use new wires as much as possible | Responsibility system for blasting device receiving and use records | Blasting technician |
| 2   | Wire continuity check must be performed | Safety operation regulations for blasting | Blasting technician |
| 3   | The detonating charge shall be placed in strict accordance with the design and construction specifications | Safety operation regulations for blasting | Blasting technician |
| 4   | Strictly control the entry of a damp detonating charge | Entry inspection system for blasting materials | Safety inspector |
| 5   | The same blasting network must use electric detonators from the same factory, from the same batch and of the same model Explosives must be waterproofed | Responsibility system for blasting device receiving and use records | Safety inspector |
| 6   | Strictly control the detonating charge stored for too long | Safety operation regulations for blasting | Safety inspector |
| 7   | Strictly control explosives stored for too long | Safety operation regulations for blasting | Blasting technician |
| 8   | Check the detonating current | Safety operation regulations for blasting | Safety inspector |
| 9   | Rationalize charge structure design | Safety operation regulations for blasting | Safety inspector |
| 10  | Strengthen the technical training for detonating operators | Safety education and training system for operators | Safety management department |
| 11  | Ensure that the detonator is fully powered | Entry inspection system for blasting materials | Blasting technician |
| 12  | Strictly follow the designed charge density to ensure that the charging force is appropriate The sundries around the blast hole shall be fully cleaned before charging | Safety operation regulations for blasting | Blasting technician |
and key risk factors at the end of the process. Second, quantitative analysis of the node risk should be realized. For refined safety management, the technique consists of implementing the safety management system via clear responsibility in the process and improving the risk clear measure plan by conducting “bottom-up” quantitative analysis of the node risk. Finally, the implementation of refined control is realized. The goal of refined implementation is to implement safety responsibility, safety measures, daily safety supervision, etc. and to continuously implement the accident accountability system.

V. CONCLUSION
To address the shortcomings of traditional accident analysis methods in the quantitative calculation and analysis of unsafe behaviours, this paper proposes an EG-based probabilistic multi-programming reasoning accident analysis method. This method can provide a reasonable explanation for the top accident causes by calculating the event logical relationship and occurrence probability and by classifying the basic events that need multi-objective control. Thus, its practical application value is ideal.

1) Taking an underground electric locomotive collision accident as an example, the explanation set of 14 event observations and their importance to the top goal are obtained. The EG algorithm can clearly reveal all the explanation sets leading to the realization of the top objectives and their importance ranking to locate the accident-causing section and to conduct accident prevention with emphasis.

2) By checking the critical importance coefficient, the importance of the explanation set obtained by the EG algorithm is demonstrated. The results show that the EG-based planning recognition algorithm is feasible for accident behaviour analysis. Compared with the critical importance coefficient, the EG algorithm provides a more explicit ranking for the importance of basic events.

3) The cross-functional flow chart method is applied to construct the node diagram of the blasting operation process, and the risk attribute of the node “inspection and analysis of blind shots D20” is described and identified qualitatively by using the risk attribute characteristics of the process node. The risk factor analysis of the node “inspection and analysis of blind shots D20” s conducted by using the behaviour planning identification method, and the refined implementation table of blind shot risk control is improved. Through the refined and effective control and visual management of small risks, the safety of the whole blasting operation process can be ensured.

4) To address the production safety problems of underground mines, the EG-PMPA model emphasizes the process of safety management by combining the process and refined management ideas, and it conducts management of the entire staff and the whole process, facilitating the identification of numerous hidden risks and problems and clearly positioning the accidental sections. The refined management framework of process node safety provides a theoretical basis for the further realization of systematic and scientific information management in underground mines. Risk data are the basis of model analysis. With the support of a big data cloud management platform, the application of risk analysis combining artificial intelligence algorithms and EG-PMPA to future research and practice will help achieve efficient safety management.

ACKNOWLEDGMENT
Chun Yang wishes to convey his gratitude for the financial support of the China Scholarship Council.

DATA AVAILABILITY
All data in this paper are available from the corresponding author upon reasonable request.

REFERENCES
[1] L. Leonard, “Examining civil society social capital relations against mining development for local sustainability: The case of Dullstroom, Mpumulanga, South Africa,” Sustain. Develop., vol. 27, no. 3, pp. 289–295, Sep. 2018, doi: 10.1002/sd.1189.
[2] I. Karidio and D. Talbot, “Controversy in mining development: A study of the defensive strategies of a mining company,” J. Sustain. Finance Investment, vol. 10, no. 1, pp. 18–43, Aug. 2019, doi: 10.1080/20430795.2019.1657315.
[3] T. Wolfsberger, M. Pinkel, S. Polansek, R. Sarc, R. Hermann, and R. Pomberger, “Landfill mining: Development of a cost simulation model,” Waste Manage. Res., vol. 34, no. 4, pp. 356–367, Feb. 2016, doi: 10.1177/0734242x16628980.
[4] J. Ge, K. Xu, X. Zheng, X. Yao, Q. Xu, and B. Zhang, “The main challenges of science safety,” Saf. Sci., vol. 118, pp. 119–125, Oct. 2019, doi: 10.1016/j.ssci.2019.05.006.
[5] E. Stemn, C. Bofinger, D. Cliff, and M. E. Hassall, “Examining the relationship between safety culture maturity and safety performance of the mining industry,” Saf. Sci., vol. 113, pp. 345–355, Mar. 2019, doi: 10.1016/j.ssci.2018.12.008.
[6] National Bureau of Statistics of China. The 2019 Statistical Bulletin of the People’s Republic of China on the National Economic and Social Development. Accessed: Aug. 10, 2020. [Online]. Available: http://www.stats.gov.cn/tjsj/zxfb/202002/t20200228_1728913.html
[7] J. H. Saleh and A. M. Cummings, “Safety in the mining industry and the unfinished legacy of mining accidents: Safety levers and defense-in-depth for addressing mining hazards,” Saf. Sci., vol. 49, no. 6, pp. 764–777, Jul. 2011, doi: 10.1016/j.ssci.2011.02.017.
[8] P. Burgherr and S. Hirschberg, “Assessment of severe accident risks in the Chinese coal chain,” Int. J. Risk Assessment Manage., vol. 7, no. 8, pp. 1157–1175, Oct. 2007, doi: 10.1504/IJRAM.2007.015299.
[9] J. Zhang, D. Cliff, K. Xu, and G. You, “Focusing on the patterns and characteristics of extraordinarily severe gas explosion accidents in Chinese coal mines,” Process Saf. Environ. Protection, vol. 117, pp. 390–398, Jul. 2018, doi: 10.1016/j.psep.2018.05.002.
[10] Y. Xiao, D. Chen, S. Wei, Q. Li, H. Wang, and M. Xu, “Rumor propagation dynamic model based on evolutionary game and anti-rumor,” Nonlinear Dyn., vol. 95, no. 1, pp. 523–539, Nov. 2018, doi: 10.1007/s11071-018-4579-1.
[11] Y. Xiao, Q. Yang, C. Sang, and Y. Liu, “Rumor diffusion model based on representation learning and anti-rumor,” IEEE Trans. Netw. Service Manage., vol. 17, no. 3, pp. 1910–1923, Sep. 2020, doi: 10.1109/tmsm.2020.2994141.
[12] Y. Xiao, W. Li, S. Qiang, Q. Li, H. Xiao, and Y. Liu, “A rumor & anti-rumor propagation model based on data enhancement and evolutionary game,” IEEE Trans. Emerg. Topics Comput., early access, Oct. 27, 2019, doi: 10.1109/etc.2020.3054188.
CHUN YANG received the B.S. and M.S. degrees in mining engineering from the Central South University, Changsha, China, in 2014 and 2017, respectively, where he is currently pursuing the Ph.D. degree with the School of Resources and Safety Engineering. His current research interests include rock mechanics, numerical modeling, and rock breaking.

KE ZHU received the B.S. degree in safety technology and engineering from Chongqing University, Chongqing, China, in 2014, and the M.S. degree in safety engineering from the Central South University, Changsha, China, in 2017. Her research interests include risk analysis and safety science.