Ph.D. Dissertation

Charan

Qualitative and Quantitative Approaches for Evaluation of Safety Risks in Coal Mines

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by

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under the guidance of

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Certificate of Examination

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We the below signed, after checking the dissertation mentioned above and the official record books of the student, hereby state our approval of the dissertation submitted in partial fulfillment of the requirements of the degree of *Doctor of Philosophy* in *Mining Engineering* at *National Institute of Technology Rourkela*. We are satisfied with the volume, quality, correctness, and originality of the work.

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This is to certify that the work presented in the dissertation entitled "**Qualitative and Quantitative Approaches for Evaluation of Safety Risks in Coal Mines"** submitted by **Charan Kumar Ala**, Roll Number 513MN1020, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of **Doctor of Philosophy in Mining Engineering.** Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

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Dedicated to my family

Declaration of Originality

I, *Charan Kumar Ala*, Roll Number *513MN1020* hereby declare that this dissertation entitled **“Qualitative and Quantitative Approaches for Evaluation of Safety Risks in Coal Mines”** presents my original work carried out as a doctoral student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section “References”.

I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation. I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

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Abstract

The safety in underground coal mines continues to be a major problem in the Indian mining industry. Despite significant measures taken by the Directorate General of Mines Safety (DGMS) to reduce the number of mining accidents in underground coal mines, the number remains high. To improve the safety conditions, it has become a prerequisite to performing risk assessment for various operations in Indian mines. It is noted that many research studies conducted in the past are limited to either statistical analysis of accidents or study of single equipment or operation using qualitative and quantitative techniques. Limited work has been done to identify, analyse, and evaluate the safety risks of a complete underground coal mine in India.

The present study attempts to determine the appropriate qualitative and quantitative risk assessment approaches for the evaluation of safety risks in Indian underground coal mines. This thesis addresses several important objectives as (i) to identify the type of safety risk analysis techniques suitable for evaluating various mining scenarios (ii) to identify and analyse the hazard factors and hazardous events that affects the safety in underground coal using the qualitative and quantitative approaches (iii) to evaluate the risk level (RL) of the hazardous factors/groups, hazardous events, and the overall mine using the proposed methodology.

In this research work, the qualitative techniques, i.e. Failure Mode and Effects Analysis (FMEA), Workplace Risk Assessment and Control (WRAC), and the quantitative techniques, i.e. Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) were applied in an underground coal mine to identify and analyse the hazard factors and hazard events. The analysis of FMEA and WRAC results concluded that the qualitative risk assessment is easy to execute and practical as they are not dependent on the historical data; rather they need experience and close examination. On the other hand, they may yield subjective results due to instinctive human assessment. The analysis of the FTA and ETA results concluded that the quantitative risk assessment could not be performed in Indian underground coal mines due to lack of probability, exposure, and consequence data.

To overcome the mentioned problems in qualitative and quantitative techniques, a methodology was proposed for evaluation of the safety risks of hazard events, hazard groups, and overall mine. The proposed methodology is the unification of fuzzy logic, VIKOR (In Serbia: VIseKriterijumska Optimizacija I Kompromisno Resenje, that means: Multi-criteria Optimization and Compromise Solution), and Analytic Hierarchy Process (AHP) techniques. Because of the imprecise nature of the information available in the mining industry, fuzzy logic was employed to evaluate the risk of each hazardous event in terms of consequence, exposure, and probability. VIKOR as was used to rank the evaluated risk of hazardous events. AHP technique helps to determine the relative importance of the risk factors. Therefore, AHP technique was integrated into the risk model so that the risk evaluation can progress from hazardous event level to hazard factor level and finally to overall mine level. To reduce the calculation time significantly and to increase the speed of the proposed risk assessment process, a user-friendly Graphical User Interface (TRAM) was developed using the C# language through Microsoft Visual Studio 2015 and .Net libraries.

The proposed methodology developed in this thesis was applied to six underground coal mines. The results presented the risk level of hazard events, hazards groups and overall mine of six mines. The mine-5 has the highest risk level among the evaluated mines. The ranking order of the mines observed based on the overall risk level is mine-5> mine-1 > mine-2 > mine-3 > mine-6 > mine-4. The results of the proposed methodology were compared with DGMS proposed rapid ranking method. This is observed that the proposed methodology presents better evaluation than other approaches. This study could help the mine management to prepare safety measures based on the risk rankings obtained. It may also aid to evaluate accurate risk levels with identified hazards while preparing risk management plans.

Keywords: Safety risk assessment; Coal mine; FMEA; WRAC, FTA; ETA; Fuzzy logic; AHP; VIKOR; Graphical User Interface.

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LIST OF ABBREVIATIONS

AHP	:	Analytic Hierarchy Process
BCCL	:	Bharat Coking Coal Limited
C	:	Consequence
C.I	:	Consistency Index
C.R	:	Consistency Ratio
CIL	:	Coal India Limited
CDS	:	Communication Dispatch System
CHP	:	Coal Handling Plant
DGMS	:	Directorate General of Mines Safety
E	:	Exposure
ETA	:	Event Tree Analysis
FMEA	:	Failure Mode and Effects Analysis
FMECA	:	Failure Mode, Effects and Criticality Analysis
FTA	:	Fault Tree Analysis
GUI	:	Graphical User Interface
HAZOP	:	Hazard and Operability study
ILO	:	International Labour Organization
ISO	:	International Organization for Standardization
LHD	:	Load Haul Dumper
MCDM	:	Multi Criteria Decision Making
MSHA	:	Mine Safety and Health Administration
MFs	:	Membership Functions
MCL	:	Mahanadi Coalfields Limited
P	:	Probability
Q	:	Ideal Solution index
RLs	:	Risk Levels
RL_{HG}	:	Risk Level at hazardous group level
R.I	:	Random Index
RMR	:	Rock Mass Rating
SSR	:	Systematic Support Rules
SMP	:	Safety Management Plan
SECL	:	South Eastern Coalfields Limited
SMS	:	Safety Management System
SDL	:	Side Discharge Loader
TOPSIS	:	Technique for Order of Preference by Similarity to Ideal Solution
TRAM	:	Tool for Risk Assessment in Mines
VIKOR	:	In Serbia: VIseKriterijumska Optimizacija I Kompromisno Resenje, that means: Multi-criteria Optimization and Compromise Solution
W	:	Weight
WRAC	:	Workplace Risk Assessment and Control

CHAPTER 1

INTRODUCTION

1.1. Background of the Problem

As per International Labour Organization (ILO) (2018), more than 2.78 million workers die every year due to occupational accidents or work-related injuries. Furthermore, 374 million non-fatal work-related injuries or illnesses occur each year. Mining is renowned for being one of the most hazardous sectors in the world due to its inherent hazards and complex work environment. Mines are categorised as coal and non-coal and further subdivided into underground and surface mines. Analysis of fatal and serious accidents data in Indian mining industry during the years 2001–2017 is shown in Figure 1.1. Figure 1.1 (a) revealed that coal mining has the highest accident rate in 2017 as compared to other mining sectors. Figure 1.1 (b) revealed that the number of fatal and serious accidents in underground coal mines is higher than opencast coal mines (DGMS, 2018).

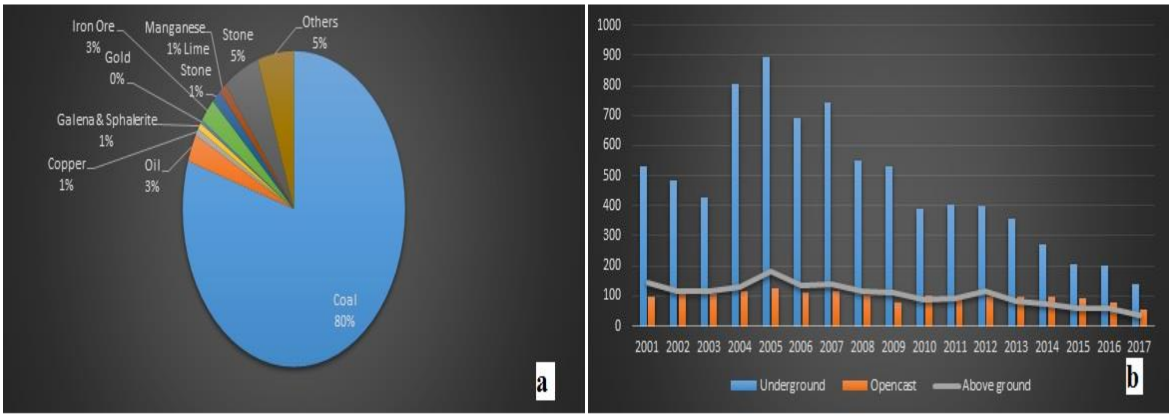


Figure 1.1 Analysis of fatal and serious accidents in Indian mines (a) by major mineral (b) mine type

After the nationalisation of coal mines in India, there was a sharp fall in the frequency rate of the accidents. In India, the DGMS has focused on prevention of accidents or incidents through rules, training and procedures and has achieved considerable success. Fatality rate and serious rate trends of coal mine accidents are represented in Figure 1.2 (DGMS, 2018). From the Figure 1.2 (a), one can observe that the death rate per 1000 persons employed was almost stagnant in the 80s and 90s. Consequently, to further improve the safety in mines, a tripartite forum at Ninth Conference on Safety in Mines held at New Delhi on February 2-3, 2000 has recommended for undertaking a formal risk assessment process aimed at reducing the likelihood and consequence of all kinds of accidents in mines (Padhi, 2004; Paliwal & Jain, 2001). The analysis of accident statistics after the introduction of Safety Management concepts in the Indian coal mines as represented in Figure 1.2 (b), (c), (d) revealed that there is a slightly decreasing trend in serious injury rate per 1000 persons employed and fatality rate per million tonnes production from 2001 to 2017. However, Figure 1.2 (b) reveals that the trend of fatality rates per 1000 persons employed is remained almost horizontal from 2001 to 2017. Although there has been significant progress in the coal mine safety since past few years; the present-day rate of accidents is still unacceptable. This reflects the gaps in current strategies employed in Indian mining industry and point out the requirement in adopting appropriate strategies to make mining safe.

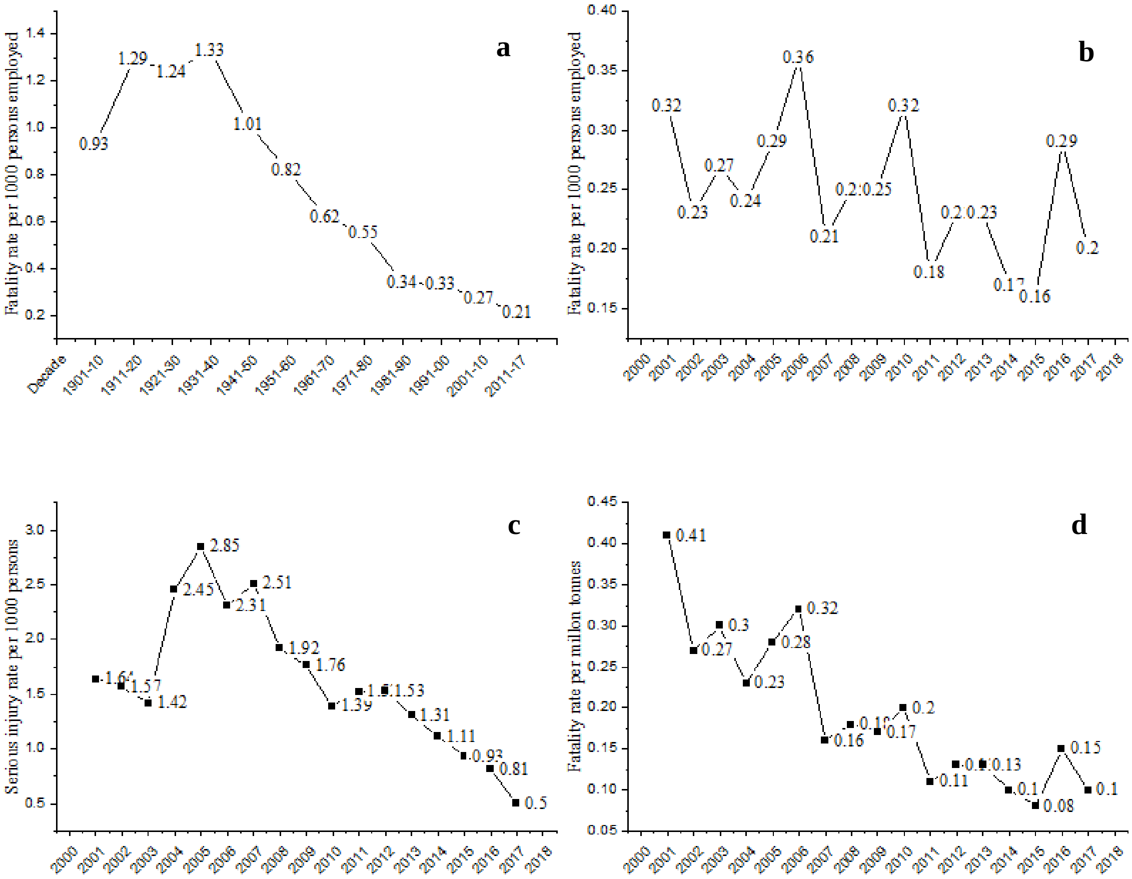


Figure 1.2 Fatality and serious injury rates in Indian coal mines

1.2. Statement of the Problem

Dynamic work process in the underground mining operations introduce not only safety issues but also health and environmental issues. The underground mine workers are exposed to various health and environmental hazards due to noise, dust, toxic gases and radiation. The health and environment factors may also create safety issues for the workers in the mine. For example, exposure of mineworkers to high levels of noise may lead to temporary/permanent noise induced hearing loss and may affect worker’s behaviour at the workplace. Short/long term exposure to radiation may cause cancer. The health issues of the mineworker may affect the performance of the worker and production of the mine and may increase the likelihood of performing unsafe acts. Short-term exposure to toxic gases lead to illness and continuous exposure to toxic gases lead to death. Environmental factor like, poor mine ventilation may lead to accumulation of methane in the workplace and may result in methane explosion in coal mines, which may result in loss of life and property. Long-term inhalation of dust can cause health risk and pneumoconiosis that affects the performance of workers.

Safety is one of the important issues in Indian underground coal mines, given that it deals with the safety of approximately 160000 employees (DGMS, 2015). Workers in underground coal mines are prone to several risk conditions during working which may endanger/cause loss of life, serious injury with the direct and indirect cost to employees and employers. Accidents in underground mines can often have serious catastrophic consequences. Because of the accidents in underground coal mines, the following consequences may arise:

- Loss of lives and human suffering;
- Inconvenience caused to injured people and others;
- Compensation paid to the deceased family;
- Compensation paid for medical treatment and disability payments; and
- Production loss.

Most of the mining accidents are preventable – they do not just happen; they are caused. Unsafe acts and unsafe conditions of work lead to accidents in underground coal mines (Tripathy, 1999, 2010; Tripathy & Patra, 1998; Zhang et al., 2018). Accidents usually occur as a combination of factors. The three main factors being the worker’s environment, the equipment, and the worker (Guha & Gangopadhyay, 2001). Many hidden factors cause accidents (Ridley & Channing, 2003). The hidden factors may include active causes, latent causes and indirect causes, which contribute to mine accidents or incidents. The fact is that underground coal mining is inherent of hazards and therefore complete elimination of risks is inevitable. Identifying, ranking and targeting the hazard, which causes mine accidents or incidents and developing mitigation measures and controls on these hazards, can prevent such mine accidents or incidents. To regulate the hazards in mines, application of safety risk management has been proposed, implemented and mandated by Australian, New Zealand, Canada, UK, USA and South African mining industries over the last few decades. In Indian mining industry, it was mandated only after the revision of the Coal Mines Regulations in 2017 (Ministry of Labour and Employment, 2017).

An effective risk assessment is required to develop practical risk management. The essential elements of risk assessment are hazard identification, risk analysis, and risk evaluation. Though the framework of the risk management is similar in all the practising countries, the risk assessment techniques used for evaluation are different as each technique has its own purpose and outcome. Marhavilas et al. (2011) stated that there are many appropriate risk assessment techniques for any circumstance and the choice has become more a matter of taste.

Joy (2004) stated that the qualitative risk assessment is commonly preferred in the Australian mining industry. Some research studies have shown that Rapid Ranking Method is the only qualitative technique adopted in Indian mining industry (DGMS, 2002, 2016; Guha & Gangopadhyay, 2001; Verma & Chaudhari, 2016b) and a very little research has been done in the area of application of risk assessment techniques for underground mining operations. As the outcome of the different risk assessment techniques varies, it is necessary to investigate safety risk in Indian underground coal mines using different qualitative and quantitative risk assessment techniques.

The qualitative and quantitative risk assessment techniques were actually developed for very hazardous industries. Extensive literature is available on the area of application of risk assessment techniques for hazardous industries (An et al., 2011; Marhavilas et al., 2011; Verma & Chaudhari, 2016b; Zeng et al., 2007). This available literature summarizes that the qualitative techniques only produce subjective results and the quantitative techniques are highly dependent on the availability of the accident or incident data. Unfortunately, in the present Indian mining industry, such data are hard to collect or may not exist. This shows that it is hard to conduct a probabilistic risk assessment in Indian mining industry. Therefore, it is necessary to develop a new risk assessment methodology to assess safety risks in underground coal mines.

1.3. Objectives and Scope of the Study

The main aim of this research is to determine an appropriate risk assessment technique for evaluation of safety risk in Indian underground coal mines. To address the research issues mentioned above, the following objectives are established in this thesis:

- To assess safety risks in underground coal mines qualitatively using FMEA and WRAC techniques.
- To assess safety risks in underground coal mines quantitatively using FTA and ETA techniques.
- To develop a risk assessment methodology for evaluation of safety risks in large underground coal mines using fuzzy logic, VIKOR, and AHP techniques.
- To develop graphical user interface for risk assessment in underground coal mines.

1.4. Plan of the Study

To accomplish the objectives of the thesis, the work was planned in the following steps:

- Visited Mahanadi Coalfields Limited (MCL), South Eastern Coalfields Limited (SECL), Bharat Coking Coal Limited (BCCL), Coal India Limited (CIL), and DGMS headquarters to gain knowledge on the risk assessment methodologies that are being used in Indian mines and to collect the accidents data.
- Identified the possible risk factors and hazards responsible for accidents based on the extensive literature survey, field investigation, and data collection.
- Identified the qualitative and quantitative risk assessment techniques suitable for the mining industry from the extensive literature survey.
- Used the FMEA, WRAC, FTA and ETA techniques to identify hazards and to evaluate safety risks.
- Developed a new methodology with an aim to overcome the drawbacks of qualitative and quantitative risk assessment techniques applied in this study.
- Developed questionnaires to assess the risk factors influencing safety in mines.
- Visited some accident-prone mines for the interview of workers with the help of developed questionnaires and discussions with the safety officer/mine management and safety officials in the studied mines.
- Assess the risk level of the studied mines using the data collected from the developed questionnaires.
- Developed a Graphical User Interface (GUI) for the new methodology in C# to reduce the computational time and to increase the speed of risk assessment process.

1.5. Organization of the Thesis

The research work undertaken in this study (evaluation and prioritization of safety risks in underground coal mines) falls within the extensive area of safety management systems. The research work carried out is presented in six chapters and the structure of the thesis is represented in Figure 1.3. A chapter wise summary of the thesis is given below:

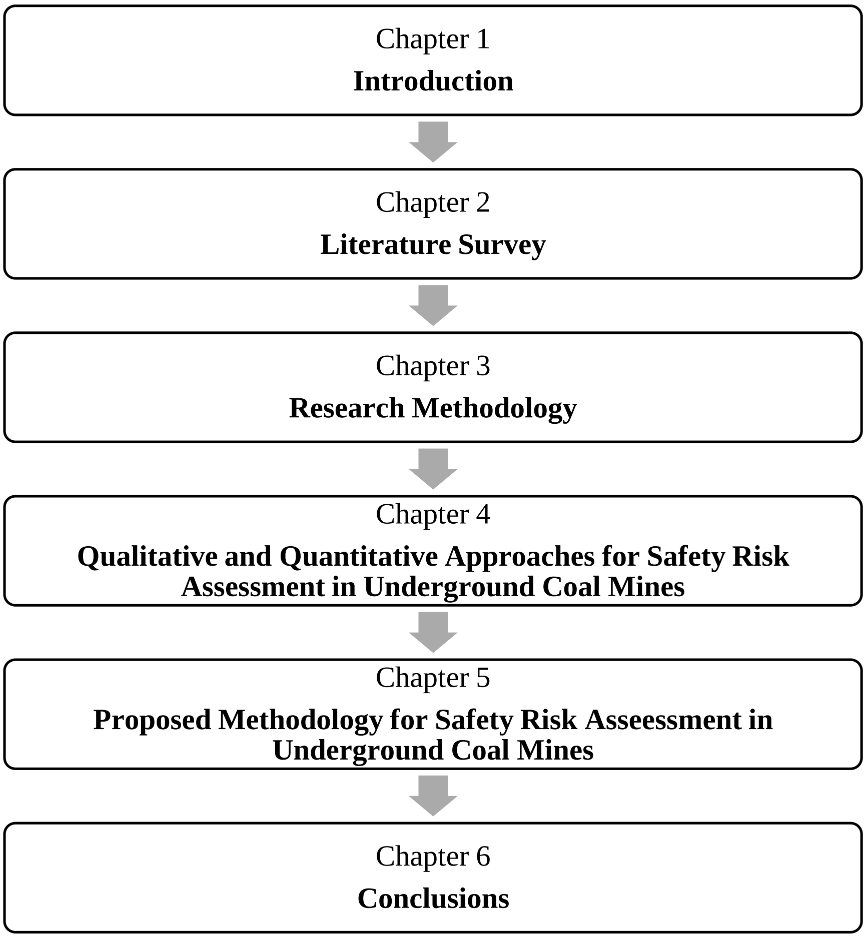


Figure 1.3 Structure of the thesis

- **Chapter 1 (Introduction):**

This chapter presents the background and statement of the problem, objectives and plan of the present study and the organization of the thesis.

- **Chapter 2 (Literature Survey):**

This chapter presents the comprehensive review of literature carried out by global researchers, academicians and mining organizations on hazard identification, safety risk analysis and risk management in the mining industry for evaluation of safety risks in underground coal mines.

- **Chapter 3 (Research Methodology):**

This chapter describes the comprehensive methodology developed for evaluating safety risks in underground coal mines. This includes the outline of the FMEA, WRAC, FTA, ETA and proposed methodology. The description of the preliminary, design, fuzzy logic-risk estimation, VIKOR-risk prioritization, and AHP-risk evaluation stages of the proposed methodology were presented. The details of the study area and the application of the comprehensive methodology developed is also presented.

- **Chapter 4 (Qualitative and Quantitative Approaches for Safety Risk Assessment in Underground Coal Mines):**

This chapter deals with the results and discussions of the qualitative and quantitative risk assessment approaches, i.e. FMEA, WRAC, and FTA, ETA applied to mine-1.

- **Chapter 5 (Proposed Methodology for Safety Risk Assessment in Underground Coal Mines):**

This chapter describes the application stages of the proposed methodology to the mines and the modules of the GUI developed. This chapter also deals with the results and discussions of the proposed methodology applied to evaluate the safety risks at hazardous event level, hazardous group level and overall mine level in mine-1, mine-2, mine-3, mine-4, mine-5, and mine-6.

- **Chapter 6 (Conclusions):**

This chapter presents the conclusions drawn from the research work. This chapter also outlines the contribution of the work for the mining industry and future scope of the study.

CHAPTER 2

LITERATURE SURVEY

2.1. Introduction

This chapter presents the comprehensive review of literature carried out by global researchers, academicians, and mining organizations on hazard identification, safety risk analysis and risk management in the mining industry for evaluation of safety risks in underground coal mines. This extensive review aims to identify the hazard sources/factors that influence the safety in underground mines, to categorize literature of the risk analysis techniques and to gain knowledge on the status of the safety risk management in the mining industry. It is also aimed to identify the research problems related to qualitative and quantitative risk analysis techniques, which would form the basis for developing a methodology for assessing risks in underground coal mines. The research objectives are established based on the critical review of the literature and the research problems identified therein.

2.2. Overview of Safety Risk Assessment and Management System

Safety risk assessment and management is a systematic approach taken to eliminate or mitigate risk, by identifying hazards and implementing controls in the workplace (DGMS, 2002). In simple terms, risk management is a thorough analysis of what could cause harm in an activity, so that one can review the current precautions taken and increase if required to prevent harm. Over the years, different industries and various international organization for standards have developed varieties of risk management standards and guidelines. As most of the developed standards and guidelines are based on specific industry experience, their goals, methodology and definition vary from industry to industry. Presently, risk management is present in almost all type of industries.

Komljenovic and Kecojevic (2007) did an in-depth bibliographic review of various risk management and assessment techniques used in different industries and represented that few standards and guides were generic and can be applied in any industry. The design and implication of the risk management system were influenced by the varying needs of an organization and its specificities (Komljenovic et al., 2008). AS/NZS 4360: 1999 was revised in 2004 (AS/NZS, 2004) and now replaced by International Standard (ISO 31000, 2009, 2018). The International Organization for Standardization (ISO) has presented applicability of 31 risk assessment tools in risk management standards (IEC 31010, 2009; ISO 31000, 2018).

WRAC, FMEA, Hazard and Operability Study (HAZOP), 5×5-risk matrix, preliminary hazard analysis, bow-tie analysis, FTA and ETA are the popular risk analysis techniques included in the mining risk management guidelines like NSWDTI (2011), Joy and Griffiths (2007) and Iannacchione et al. (2008). DGMS (2002) recommended adopting rapid ranking method (also known as Fine-Kinney method) in the Indian mining industry. Sabir et al. (2012) developed a 5×5-risk matrix for use in CIL, a major public sector company. DGMS (2014a, 2014b) promoted the use of personal risk assessment (Take 5) and 5×5-risk matrix.

2.2.1. Definition of terms used in safety risk management

2.2.1.1. Hazard

ISO vocabulary guide (2009) defined "hazard as a potential source of harm, injury or loss". Hazard source is a location or a condition that gives rise to a hazard. A hazardous event is a situation that can lead to the presence of a hazard. The workplace hazards can be classified as health hazards, safety hazards, biological hazards, chemical hazards, ergonomic hazards, physical hazards, environmental hazards, and economic hazards (CCOHS, 2017; OSHA, 2017; Tchankova, 2002). Safety hazards in mines may arise from worker's unsafe acts or unsafe practices or unfit equipment or unsafe working conditions.

2.2.1.2. Safety

Safety is defined as a state in which the risk of harm to persons or damage to property is limited to a tolerable level (IS: 18001, 2007). To define and to evaluate the safety, it is essential to link safety with risk, as safety is not quantifiable. A high level of risk corresponds to low safety, and a low level of risk corresponds to high safety (Suddle, 2009). The advantage of linking safety to risk is, risk can be quantified and evaluated to check whether the risk level is acceptable or not.

2.2.1.3. Risk

The risk is defined as the chance of something happening that will have an impact on the objectives (HB 436, 2004). Fundamentally, the risk is the chance that a safety hazard will result in an unwanted accident or incident. Mathematically, the risk is the probability that the exposed hazard will result in the accident and consequences. Fine (1971) devised the mathematical formula for risk score as shown in equation 2.1:

$$\text{Risk Score} = \text{Consequence} \times \text{Exposure} \times \text{Probability} \tag{2.1}$$

Where, Consequence is the most probable results of a potential accident, including injuries and property damage. Exposure is the frequency of occurrence of the hazard-event. Hazard event is the undesired event, which could start the accident-sequence. Probability is the likelihood that, once the hazard-event occurs, the complete accident-sequence of events will follow with the necessary timing and coincidence to result in the accident and consequences.

2.2.2. Risk assessment in safety risk management

2.2.2.1. Hazard identification

The hazard identification step aims to generate a complete list of hazards and their associated risks that might have an impact on the success of each of the objectives identified in the context stage (ISO 31000, 2018). To identify risk, one must first know what hazards are present, and what potential harm is associated with the hazard. Therefore, hazard identification is used instead of risk identification. Canadian Standards Association (CAN/CSA, 2000) spelt out hazard identification as “the process of determining that a hazard exists and defining its characteristic”.

The process of hazard identification is possibly the most crucial step of the risk assessment process, as the main causes are identified in this step only and when a cause is not identified, it cannot be actively managed (Greene & Trieschmann, 1981; Sabir et al., 2012; Tchankova, 2002). The common hazard identification techniques are shown in Table 2.1 (Glossop et al., 2000; Mannan, 2012).

As most of the hazard identification techniques are generic, they can be used to identify hazards in any workplace. However, hazards may vary from one workplace to another and that is the reason why skilled experts experience is essential to identify all the hazards in a given workplace accurately. The hazard identification process should consider the entire life cycle of job and potential impacts on workers, machine and environment. A systematic process starts at the objectives of the context establishment to generate a comprehensive list of hazards. The general steps in hazard identification are as follows (HB 436, 2004):

- Select the job to be evaluated,

- Divide the job into necessary steps,
- Develop the list of expected hazards associated with each step of the job, and
- Develop the list of risks associated with the identified hazards.

Table 2.1 Hazard identification techniques

Informal Approach	Formal Approach
Checklists	Failure Mode and Effects Analysis
What-If analysis	Event Tree Analysis
Historical accident and incident records	Fault Tree Analysis
Personal observation, interviews	Workplace Risk Assessment and Control
Safety committee meetings, informal meetings	Job Hazard Analysis
Personal experience	Bow-Tie Analysis
Brainstorming	Management Oversight Risk Tree
Consultation with workers	Preliminary Hazard Analysis
Safety audits	Hierarchical Task Analysis
	Hazard Identification and Ranking
	HAZOP
	Hazard Identification - HAZID

2.2.2.2. Risk analysis

Risk analysis is about developing an understanding of the risks associated with the hazards identified during the hazard identification process (ISO 31000, 2018). Risks associated with the identified hazards need to be assessed to find out the severity of the risk with the current controls employed. Risk should be assessed considering the following three elements:

- Exposure to the hazard causing an accident,
- Consequences arising from the accident, and
- Probability of the accident.

Based on the assessment of these three elements, the risks of the identified hazards are calculated and ranked. The risk analysis process provides an input to risk evaluation step and helps employers to make decisions as to what risks or hazards need to be controlled by selecting the appropriate risk treatment strategies and methods. Risk analysis may be carried out to a varying degree of detail, depending upon the risk, the purpose of the analysis and the data, information and resources available (HB 436, 2004). Tixier et al. (2002) studied risk analysis methodologies and categorized them into two groups: qualitative and quantitative techniques. Qualitative risk assessment techniques use relative values for consequence and probability to evaluate the level of risk in terms of high, medium, and low levels. They are based both on systematic estimation process and experience of the expert, and they are more suitable to calculate low complex systems. On the other hand, quantitative risk assessment techniques use actual statistical values for consequence and probability to evaluate the level of risk. They are suitable for highly complex systems (IEC: 31010, 2009; Marhavilas et al., 2011; Ramona, 2011). The operation of the risk assessment techniques is presented in many works of literature (Ayyub, 2014; Bahr, 2014; Ericson, 2005; Harms-Ringdahl, 2003; ILO, 2013; Mannan, 2012; Tripathy, 1999, 2010).

The popular qualitative techniques are FMEA (BSI, 1991a; Dhillon, 1992; MIL-STD, 1980; Stamatis, 2003); WRAC (Joy, 1994; Sabir et al., 2012; Vivek et al., 2015). The popular quantitative techniques are FTA (BSI, 1991b; Ericson, 1999; Lee et al., 1985; Marhavilas et al., 2014; Reniers et al., 2005; Vesely et al., 1981); ETA (Beim & Hobbs, 1997; Hong et al., 2009; Marhavilas et al., 2014). In techniques like FTA, ETA, FMEA and WRAC, hazard identification is the starting point and the risk analysis is the final output.

2.2.2.3. Risk evaluation

The risk evaluation aims to make decisions, based on the results of risk analysis, about which risks need treatment and treatment priorities (ISO 31000, 2018). In the risk evaluation process, the level of risk found during the evaluation is compared with the risk criteria established in the context stage. If the level of risk is low or negligible, then the risk evaluation can lead to a decision to continue the existing controls and not to treat the risk. If the level of risk is medium or high, then the risk evaluation can lead to a decision about the risk treatment controls to be implemented to reduce or eliminate the risk. In some cases, further analysis may be needed (ISO 31000, 2018).

2.2.3. Safety risk management process

The safety risk management process that allows the systematic identification of hazards to the implementation of risk controls, communication and monitoring for control effectiveness is shown in Figure 2.1 (IS: 18001, 2007; ISO 31000, 2018). Establishing the context, risk assessment and risk treatment are the three major processes in the safety risk management system. The following tasks are involved in the context establishment phase (ISO 31000, 2018; Mullai, 2006):

- Define the task,
- Select a risk analysis team,
- Define the objectives,

- Identify the stakeholders,
- Define the external and internal parameters,
- Define the scope and limits of the task,
- Select method or technique and
- Collect data.

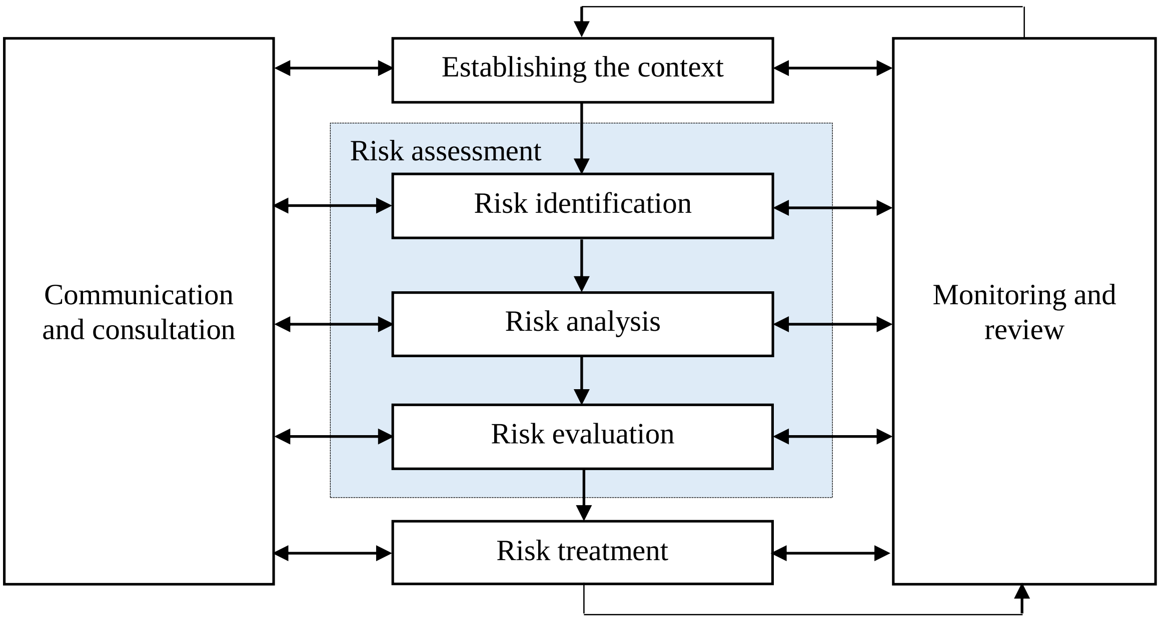


Figure 2.1 Safety risk management process

As per ISO vocabulary guide (2009), risk assessment is defined as "the overall process of risk identification, risk analysis, and risk evaluation". It aims to evaluate the potential risks associated with an activity systematically. The output of the risk assessment will be the input to the decision-making process of the industry (IEC: 31010, 2009).

Risk treatment involves identifying and evaluating treatment options for modifying risks, preparing and implementing treatment plans. The following are the risk treatment options, also known as 'Hierarchy of Controls' (NSWDTI, 2011):

Steps in Hierarchy of Controls	**Risk treatment techniques**
Elimination: completely remove the hazard.	Risk elimination
Substitution: replace the hazard.	Risk mitigation
Engineering: isolate people from hazard using engineering devices.	Risk mitigation
Administration: control the hazard using training, procedures.	Training program
Personal protective equipment's: isolate people from hazard using hard hats, boots, gloves, safety glasses, etc.	Company organization
Safe human behaviour: control the hazard with awareness, instructions, and compliance with rules and procedures.	Company organization

2.3. Hazard Identification

Presence of hazard is the main cause of the accidents as shown in Figure 2.2. As hazards are the main identifiable cause of the accidents in workplaces, its control will offer a great chance of reducing injury or accident. Therefore, prior knowledge of the type of hazards present in the workplace is required to evaluate the safety risks effectively. Rasche (2001b) presented the hazard characteristics and effects in the mining industry as presented in Table 2.2.

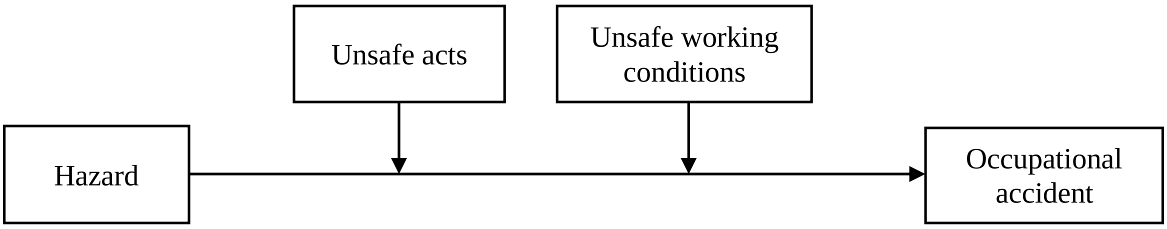


Figure 2.2 Accident mechanism

Table 2.2 Hazard characteristics and effects in the mining industry

Hazard characteristics	Effects
Single concentrated hazard sources	Often – Explosives magazines, fuel and chemical reagents storage, transportation of blasting materials throughout the mine
Distributed sources of hazards	Always – throughout the mine – geological, environmental, mechanical
Chemical toxicity	Often – beneficiation plants, reagent mixing plants, tailing dams, chronic ill health effects well documented for the mining sector
Fires	Often – mobile and fixed equipment, beneficiation plants, electrical installations, fuel and tyre storage extreme fire if fire underground
Explosions	Sometimes – results from fires, accidents from blasting or preparation of blasting agents, fuel storage, the extreme risk if fire underground
Radioactivity	Rarely – except for uranium mines and associated beneficiation plants
Changing configuration	Always – transportation of ore and waste materials, different ground conditions as mine progresses
Human error	Important
Environmental pollution potential	Considerable – regional & national, short, medium and long-term
Design considerations & physical characteristics	Complex processes with few redundancies– considerable exposure to inherent hazards (geological conditions) – facilities both above and underground – usually in remote locations. Very vulnerable to natural events – cyclones, flooding.

A hazard may originate from different sources and can take many forms. Therefore, it is essential to identify the sources of the hazards and the scenarios in which they may originate. The identification of hazard source includes an unsafe act of worker, an unsafe condition of machinery or equipment, and an unsafe working environment. The interactions among hazard sources is the source of safety issues. The hazards can be identified using two types of approaches (Kumamoto & Henlye, 1996): (i) informal approach (ii) formal approach.

The informal approaches were based on previous accident and injury data and operational history. In this approach, the data are analysed after the occurrence of an accident event. The formal approaches were based on hazard identification techniques. In this approach, the data can be analysed either before or after the occurrence of an accident event. Khanzode (2010) classified the hazard identification techniques as backward tracking, forward tracking and morphological methods. FTA is an example of backward tracking method. The hazard identification in FTA starts with an accident event and ends at determining the root causes of the accident event. ETA is an example of forward tracking method. The hazard identification in ETA starts with an initiating event selecting from the accident data and ends at developing the models of linear paths using the scenario development techniques.

In morphological methods, the search is focused on potential hazardous elements and potential targets in the work system (Khanzode, 2010). The examples of morphological methods are HAZOP, FMEA, Failure Mode, Effects and Criticality Analysis (FMECA), Energy analysis, Management Oversight and Risk Tree, Deviation analysis, Change analysis and Comparison analysis. The application of formal approaches to identify hazards in the mining industry is very rare.

2.3.1. Hazard source/factors identification

The causes of underground coal mine accidents identified from the various literature were as follows:

Leigh et al. (1990) studied the incident reports of New South Wales coal mines from 1986-1988 and identified the personal and environmental factors associated with the accident lost-time injuries. The authors concluded that the majority of the accidents in underground mines was due to various machinery or equipment.

Mandal and Sengupta (2000) analysed the fatal accidents in Indian coal mines and identified the causes of accidents coal mines. The causes identified were roof and side fall, haulage accident, conveyor accident, other transport machinery, explosives, electricity, dust and gas accident, inundation, and other accidents.

Singh and Sen (2001) stated that the main safety problems in underground mines arise from ventilation, dust and fumes, and noxious gases.

Donoghue (2004) reviewed the hazards in the mining industry and listed the common causes of fatal accidents as follows: roof fall, explosions, inundation, air blast, fires, mobile equipment accidents, fall of an object from the height and electrocution.

Padhi (2004) analysed the fatal accidents in coal mines from 1994-2001 and concluded that majority of the accidents were caused by roof fall and rope haulage.

Paul and Maiti (2005, 2008) studied the role of socio-technical and personal characteristics on work injuries in mines and concluded that socio-technical variables like social support, work hazards and safety environment were the main factors in occurrences of the accidents/ injuries in mines.

Burgess-Limerick and Steiner (2007) studied the injury narratives reported to the Mine Safety and Health Administration (MSHA) and identified five hazards associated with underground coal mining equipment. The identified hazards were rock falling from the supported roof, collisions while driving underground vehicles, incorrect operation of bolting machine controls, handling continuous miner cable and travelling in underground vehicles on rough roadways.

Iannacchione et al. (2008) presented the strata instabilities, explosions, powered haulage, fire, equipment failure and slip or fall of person as the hazard types associated with the multiple fatality events in US mineral industry.

Asia Monitor Resource Centre (2010) along with South Asian Research and Development Initiative and the International Confederation of Free Trade Unions carried out an occupational safety risk assessment in an Indian mine. Explosive gas, heat, low oxygen, roof fall, side fall, electrical hazards, presence of methane, accident due to unauthorized Side Discharge Loader (SDL) operations, haulage rope breaking, run over by coal tubs, haulage over speeding, non-availability of roller pulleys and guide pulleys, and non-provision of safety equipment were the safety hazards identified by the workers in hazard mapping exercise.

Kunar et al. (2010) assessed the job-related hazards influencing occupational accidents in two underground coal mines. The authors identified the safety issues among mine workers using an epidemiologic investigation as a risk analysis tool. The results concluded that poor working conditions, material handling and ground control were the main job-related hazards.

Khanzode et al. (2011a) studied the accident data collected over 15 months from an underground coal mine and concluded that hazards related to ground-fall, roadways, housekeeping, machinery and materials were the recurring hazards in underground coal mines.

Bhattacherjee et al. (2011), Kunar et al. (2008) listed hand tool related, material handling, machine related, environment/work-related conditions, strata control, electrical equipment, haulage and blasting as the job-related hazards in Indian underground coal mines.

Dash et al. (2017) stated that 60 accidents with 10 or more fatalities per accident have occurred in the Indian mining industry between 1901 and 2016. The main hazard sources identified were explosion (25 accidents), inundation (18 accidents), roof/side fall (11 accidents) and fire (3 accidents).

Zhang et al. (2018) analysed the accident injury data of the US mining industry from 2000 to 2016 to find the root causes of the accidents and identified 126 unsafe conditions and 98 unsafe behaviours related to electrical, explosion, fire, inundation, haulage, machinery, roof fall, and other type of accidents.

2.3.2. Hazardous events identification

The literature identified on in-depth analysis of the causes of roof fall, machinery, inundation, electricity, and dust, gas and other combustible materials is very limited.

2.3.2.1. Roof fall

Biswas and Zipf (2003) reviewed the ground fall related accidents in the US mining industry during 1984-1999 and organised them using the taxonomic analysis. The authors presented the root causes of the ground fall accidents using the taxon tree.

Based on the analysis of accidents from 1901 to 2000 in Indian mines, **Kejriwal (2002)** cited the following as the main causes for the roof and side fall accidents in Indian underground coal mines:

- the delay in securing freshly exposed roof and sides of working places;
- poor knowledge of Systematic Support Rules (SSR);
- improper inspection after shot firing;

- failure to provide a fence at the entrance of unauthorized places; and
- inadequate examination and testing of roof and sides.

2.3.2.2. Machinery

Helander et al. (1983) studied the injury data of 600 roof-bolter accident to assess the characteristics of roof bolting accidents. The common causes identified from the analysis were: rock fall on operator, struck by machine part, caught on or beneath the machine, activating a machine part resulting in injury to fellow operator, struck by flying object, slip and fall while using the machine, one-operator trams into another operator, ruptured hydraulics and lifting or pulling objects.

Ashworth et al. (1997) pointed out caught between tubs, fall of materials, coupling/uncoupling of tubs, runaway of tubs, derailment, collision of tubs, fall of roof/side, fall of men as the hazards in the rope haulage transport system.

Burgess-Limerick and Steiner (2006), Burgess-Limerick (2006, 2011) studied the injury narratives from different underground mines in New South Wales and identified hazards associated with underground coal mining equipment. The common hazards associated with underground coal equipment were being struck by and being caught between while drilling or bolting on bolting machine or continuous miner. The less common hazard with high consequence was contact with hydraulic fluid.

Dhillon (2009) reviewed the mining equipment accidents in US mining industry and presented the primary causes of equipment accidents as follows: poor ingress/egress design, restricted visibility, unguarded moving parts, poor control display layout, poor design or redesign, exposed sharp surfaces and exposed wiring and hot surfaces.

Kecojevic and Nor (2009) examined the US underground mining accident data from 1995 to 2007 to identify the hazards associated with equipment-related fatal accidents. The hazards identified for roof bolter were working under unsupported roof, failure to follow proper maintenance procedure, failure to provide safe working conditions. The hazards identified for Load Haul Dumper (LHD) were safe working conditions and failure to set parking brake/chock.

Ruff et al. (2011) examined 562 serious accidents data of the US mining industry from 2000 to 2007 to find the contributing factors to the accidents, especially equipment-related accidents. The results concluded that the most severe accidents have occurred while operating or maintaining the machines.

2.3.2.3. Electricity

Cooley and Hill (1981) applied FTA to identify the root causes of the electrical accidents in the metal and non-metal mines and suggested proper earthing practices for mine power systems.

Hill and Stanek (1981) applied the FTA and ETA to assess the safety and reliability of mine power systems. The results showed that poor design of power systems was the main cause of the majority of occurred accidents.

2.3.2.4. Spontaneous combustion and inundation

Lang and Fu-bao (2010) identified 42 influencing factors that lead to spontaneous combustion of coal seams.

Luo and Liu (2010) highlighted the importance of risk management in coal mines and pointed out that water, gas, coal dust, fire, and roof fall as the five natural disasters causing hazard factors. The authors also analysed the inundation accident in an underground coal mine and presented the causes of accident as lack of technical personnel, lack of inspection, lack of supervision, using of improper explosive devices and illegal operation of mine.

2.4. Safety Risk Analysis

The way in which risks are perceived is strongly correlated with the way in which they are calculated (Wilson & Crouch, 1987). Over the years, various researchers have proposed different safety risk analysis methodologies for evaluating the risk in the workplace. Lost-time injury rates, fatal accident rates, severity index, and occurrence probability are the common risk measures used to estimate the risk of unwanted events. Various distribution-based models were also applied to investigate the risk level in mines.

Kerkering and Mcwilliams (1987) applied the Inter-Arrival method and Maximum Likelihood Estimators to index the mine safety.

Maiti and Bhattacherjee (1999) studied the 4-year injury experience data of an underground coal mine in India and applied binary logit and multinomial logit analysis to evaluate the risk of occupational injuries to underground coal mine workers.

Maiti (2003) applied the logistic regression model to calculate the risk indices for Indian underground coal mines.

Düzgün and Einstein (2004) assessed and managed the roof fall risks of 12 underground coal mines in the Appalachian region using risk analysis and decision analysis methodology. The authors quantitatively calculated the risk of roof fall as the product of probability and consequence and managed the calculated risk using the decision analysis methodology. In this study, the authors used the time intervals between the roof fall accidents, the number of roof falls in each year data for weighing probability and the relative cost criterion of major attributes of roof fall like fatality, disability, injury, and equipment damage, and emergency operations for determination of consequence. The application of the methodology to case study mine showed that the proposed technique was a robust method for coping with uncertainties of the associated risks.

Düzgün (2005) assessed and managed the roof fall risks of five underground coal mines in Zonguldak coal basin using the methodology proposed by Düzgün and Einstein (2004).

Maiti and Khanzode (2009) developed a relative risk model for roof and side fall fatal accidents in Indian underground coal mines using a log-linear analysis of two-way contingency table. Potential failures, the relative risk of fatalities and the safety measure effectiveness were obtained as outputs of the developed model and were used as key safety performance indicators of the roof and side fall accidents in underground coal mines. The authors validated the proposed model using six years' data obtained from coal mines, and the results indicated that current safety measures in mines were mainly dependent on the safety performance, and the preventive measures were not based on the assessed risk.

Sari et al. (2009) proposed a methodology to establish stochastic modelling of accident risks associated with an underground coal mine. The authors used fitting appropriate distribution to model the frequency and consequence of the accident, calculated the risk levels using the Monte Carlo simulation and predicted using the time series analysis. One important conclusion was that the number of accidents followed a Poisson distribution. Time series analysis results showed that no change in risk level for the next five years.

Khanzode et al. (2011a) proposed a new methodology for evaluation and monitoring of recurring hazards in underground coal mines. In the proposed methodology, the authors identified the recurring hazards by using inspection reports and characterised the identified hazards in terms of Weibull-distribution based hazard rate, Poisson-distribution based cumulative risk of occurrence and monitored hazard occurrences using Weibull-distribution based control charting.

Khanzode et al. (2011b) developed an injury count model and injury risk model for the overall work system and derived five statistical indices for quantifying the occupational injury risks. The indices developed in this study were the potential number of injuries, relative risk of injury, effectiveness of safety system, estimated man-days lost and potential man-days lost.

Chen et al. (2012) studied the trend of coal mine accidents in China using the multi-dimensional statistical analysis. In this study, the authors classified the accidents as gas explosion, poisoning and suffocation, coal and gas outburst, coal dust explosion, fire, mine, inundation, roof fall, transport and hoisting accident, blasting accident and others. The authors also presented the direct causes of the accidents. The analysis results showed that the priority should be given to coal and gas outburst, mine water accident, and gas explosion while conducting safety management.

2.4.1. Safety risk analysis techniques

Researchers use risk analysis techniques to evaluate risk systematically. Risk analysis techniques are divided into two categories (i) qualitative (ii) quantitative techniques. In qualitative techniques, the probability of a risk event and consequence of the risk are calculated using the experts' judgement, and the output of the risk level was presented using non-numeric data. On the other hand, quantitative techniques are based on the past available accident data and the output of the risk level was presented using a numeric value. Few modelling techniques like FTA, ETA can be used to identify hazards and to evaluate risk either qualitatively or quantitatively.

2.4.1.1. Qualitative techniques

Nelson (1986) developed qualitative fault trees for studying the root causes of the inherent fire safety in a coal mine.

Tripathy and Patra (1998) categorised the risks associated with underground coal mines into three groups namely pre-production, production and post-production. The risks presented in the production stage were haulages, fall of materials, work with hand tools, electrocution, roof fall, explosion, machinery, noxious atmosphere, water inrush and outburst. The authors also presented scales for probability, exposure, consequence and total risk in coal mines.

Selçuk et al. (2000) evaluated the coal mine accident data using the risk assessment techniques. The analysed results concluded the causes of accidents as follows: suffocation by gases, gas and dust explosion, roof fall, fire, handling material, powered haulage, inundation, electricity, accident due to machinery, accident due to falling objects, and slip or fall of person. In this study, to evaluate the risk, frequency (number of accidents per month) was expressed as a Poisson distribution and severity (days lost) was expressed as an exponential distribution. Risk classification schemes were plotted to explain the effects of different characteristics on variation of frequency and severity.

Donoghue (2001) illustrated the qualitative and semi-quantitative risk assessment matrices. The authors used a walk-through survey of an underground metal mine to describe the qualitative risk assessment matrix and used the element from the existing epidemiological studies of hazard-disease combinations in mining and mineral processing to describe the quantitative risk assessment matrix.

Guha and Gangopadhyay (2001) presented the results of a pilot study taken to test the application of risk management in the Indian mining industry. A sample of risk rating results is shown in Table 2.3. From the results, it could be observed that multiple hazards had the same risk level, which made it hard to prioritize the hazards.

Table 2.3 Risk rating for inadequate ventilation

Hazard	Mechanism	C	E	P	Risk
Air leakage through airlock	Leakage through doors and windows	5	5	5	125
	Leakage through head gear structure	5	5	5	125
Improper distribution of air to faces	Poor workmanship in installation of brattice and ducting	5	5	5	125
	Inadequate monitoring of face ventilation	5	5	5	125
	Poor discipline on maintaining brattice and ducts	5	5	5	125

Lind (2005) conducted a risk analysis of underground coal mine pillar extraction using a 5×5-risk matrix and used Analysis of Pillar Extraction Potential (A-PEP) tool to predict the success of conducting pillar extraction. The main high hazards identified from the analysis were the presence of water, gas, massive roof conditions, goaf and pillar behaviour, panel design parameters, cutting parameters, the role of temporary supports, intersections, and pre-splitting of pillars.

Iannacchione et al. (2007) analysed the risk of roof falls in underground coal mines using a 5×5-risk matrix. The probability and consequence used in the risk matrix were based on the Roof Fall Risk Index values, and the exposure of miners to roof falls respectively. In this study, the authors used a Roof Fall Risk Index tool to identify the hazards of roof falls.

Hossaini and Behraftar (2009) assessed the roof fall risks in Kerman coalfields using the Risk Priority Number approach along with the Düzgün and Einstein (2004) proposed decision analysis methodology.

Iannacchione and Mark (2009) applied the Major Hazard Risk Assessment technique studied by the National Institute for Occupational Safety and Health to evaluate the ground control hazards associated with room and pillar retreat mining. Roof falls, rib instabilities, air blast from goaf caving event, support failure, bumps, pillar instability, the presence of gases from adjacent gob, and water from overlying abandoned mine were the ground control hazards identified. In this study, the authors applied WRAC, risk matrix techniques to analyse unwanted events, and used the Bow-Tie technique to find the existing preventive controls and necessary recovery measures.

Robertson and Shaw (2009) considered the consequence severity of the biological, land use impacts, regulatory impacts, public concern and safety issues and used FMEA technique to assess the failures of mine closure plan measures.

Shahriar and Bakhtavar (2009) used the Düzgün and Einstein (2004) proposed decision analysis methodology to assess the roof fall risks in five coal regions in Iran.

Beamish et al. (2010) demonstrated the practical application of FTA for spontaneous combustion of coal in an underground coal mine.

Ghosh (2010) evaluated the causes of injuries in an Indian an underground coal mine using the Risk Priority Number method and 5×5-risk matrix. The causes evaluated in this study were roof and side fall, slippery floor and defective shoes, hit by the tub, electrical apparatus, conveyor, drilling and dressing and haulage.

Fan et al. (2011) constructed the fault tree for analysing the mine gas explosion. The identified basic events were as follows: power failure, insufficient ventilation air quantity, failure to provide ventilation in time, gas leak, smoking, blasting flame, friction sparks and an electrical fire.

Jianmin and Renshu (2011) analysed the mine water inrush accidents using the FTA. The results of the analysis revealed that improper design, pillar failure, surface water, aquifer or goaf water, improper sump size, failure of power supply, failure of pumps, lack of knowledge of prevention and control of water, inadequate safety measures, failure of water dam were the basic events that can lead the mine water inrush accident in 90 different ways. The study also concluded that the improper design and pillar failure were the two most frequent basic events.

Pejic et al. (2013) used a semi-qualitative risk assessment and estimation method to evaluate the explosion risk in underground coal mines. The methodology consists of Fine-Kinney method and Layer of Protection Analysis. The authors used Fine-Kinney method to evaluate the risk index level for underground coal mines and Layer of Protection Analysis to find the preventive and protective measures of explosion risk. The authors had applied the proposed methodology to an underground mine and listed the organisational and technical safety measures for the reduction of consequence, probability, and exposure time factors.

Burgess-limerick et al. (2014) analysed a continuous miner accident that occurred in Queensland underground coal mine using a Bow-tie analysis.

Calizaya et al. (2014) identified the hazards associated with the use of booster fans in underground coal mines and evaluated the risks using risk matrix, WRAC, and FMEA. Fire and contaminated air recirculation were the two major hazards associated with the operation of booster fans.

Krause and Krzemień (2014) attempted to perform methane risk assessment in five underground coal mines. In this study, the authors used a heuristic methodology based on the Delphi method and a group survey by a panel of experts to evaluate the risk assessment questionnaire. The questionnaire consisted of factors shaping the methane hazards, the activity of methane ignition originators, detection and prevention of methane risk, and possible human and material losses. The results concluded that the impact of methane drainage, electrical equipment, work organization, and ventilation conditions have the most significant influence on the shaping of methane hazards in underground mines.

Kumar (2014) applied the FMEA technique to assess risk in an underground coal mine and presented the control measures based on the risk priority number. The main safety hazards identified in this study were slipping or tripping, working near water, explosives, drilling, loading, fall of roof or pillar, haulage, and ventilation.

Liu and Xue (2014) identified the root causes of main shaft accident using the FTA. The root causes identified were: bucket overload, bucket stuck, fast acceleration and deceleration, bad pulley gasket material, improper oil in pulley gasket, improper space between brake shoe and brake disc, high cylinder residual pressure in brake disc, improper quality of brake shoe material, improper oil in brake disc, jammed piston, failure of electrical control system and failure of disk spring stiffness.

Mishra and Rinne (2014) developed the guideline for managing geotechnical risks in underground coal mines. In this study, before commencing the geotechnical risk assessment, the authors applied a numerical risk-ranking method to find the suitable risk assessment process and risk assessment tools. The authors determined that WRAC, FMEA, Bow-Tie Analysis, FTA and ETA were suitable to identify the geotechnical hazards. The likelihood can be assessed using deterministic, probabilistic, or possibilistic approach and the consequence can be assessed using the accident cost model. The risk matrix was suitable for risk representation.

Bagherpour et al. (2015) attempted to assess the safety risk of Iran's underground coal mines by introducing preventive and preparative measures. In this study, the authors identified ten hazards in Iran's underground coal mines, and their related preventive and preparative measures were presented. The hazards identified were methane explosion, coal dust explosion, poisoning and suffocation, fire, roof fall or side fall, blasting, traffic accidents, water inflow, electrical, and gas burst. The authors used a questionnaire to record the probability and consequence of the identified hazards and quantified the results using a bipolar scale. The results concluded that the methane explosion, coal dust explosion, and traffic accidents were the three hazards with high-risk levels.

Behraftar et al. (2017) modified the risk priority number and defined it as the product of the degree of probability of occurrence and the degree of significance of consequence. The authors used the modified technique to assess the working risks in Iranian underground coal mines and concluded that the roof fall showed the highest risk level followed by gas poisoning.

Mishra et al. (2018) evaluated the risks associated with a conveyor belt system installed in an underground coal mine. Brainstorming and root cause analysis were carried out to find the hazards and risks involved in the evacuation of coal using the conveyor belt system. From the results, it was observed that multiple hazards like operating by unauthorized operators, belt snapping, drive head structure failure, failure of braking system, failure of take-up arrangements, have the same risk level.

2.4.1.2. Quantitative techniques

Iverson et al. (2001) investigated a dozer falling into a void in a coal dump accident using Fault Tree program on a personal computer. The quantitative study identified 15 intermediate and 28 basic events that led to the burial of the dozer and graphically represented the interrelationship between these various subordinate events as well as the chain of events leading up to the primary event. The authors also conducted a sensitivity analysis to determine the highest influence of the basic events on dozer burial in coal dump.

Gupta et al. (2006) used FTA to understand the failure logic of a longwall shearer. The FTA and ranking showed that how the maintenance priority changed over time.

Kecojevic et al. (2008) analysed the belt conveyor-related fatal accidents in the US mining industry using the data collected from MSHA from 1995 to 2006. Management's failure to provide adequate maintenance procedure, workers failure to follow adequate maintenance procedure, failure to provide over bridge, failure to use over bridge facility, adverse geological conditions, and failure of mechanical components were the six hazards identified in the hazard identification stage. The authors used quantified risk matrix to analyse the risk level of the identified hazards and concluded that failure to provide adequate maintenance procedure and failure to follow adequate maintenance procedure were the two most severe and frequent hazards.

Kecojevic et al. (2008) analysed the continuous miner-related fatal accidents in the US mining industry using the data collected from MSHA from 1995 to 2006. Failure of the victim to respect the equipment-working area, failure to identify adverse geological conditions, failure to follow adequate maintenance procedure and failure of mechanical components were the four hazards identified in the hazard identification stage. The authors used a quantified risk matrix to analyse the risk level of the identified hazards. The results concluded that failure of the victim to obey equipment working area rules was the most severe and frequent hazard.

Komljenovic et al. (2008) collected 10-year injuries data from 1995 to 2004 and systematically categorised injuries into three types: fatalities, non-fatal days-lost injuries and no-days-lost injuries. Based on the analysis of collected data, the authors proposed the severity levels, frequency levels, and a global risk analysis matrix for analysing risks in mines.

Md-Nor et al. (2008a) analysed the haul truck-related fatal accidents in the US mining industry using the data collected from MSHA from 1995 to 2006. In the hazard identification stage, the authors identified sixteen hazards and categorised them into three groups: human errors, equipment failure and working environment. The authors used a quantified risk matrix to analyse the risk level of the identified hazards. The results concluded that the risk level of the hazards: failure of mechanical/electrical/hydraulic components, failure of victim to respect the truck working area, failure to provide adequate berm at dump sites and haul roads was very high.

Md-Nor et al. (2008b) analysed the loader and dozer related fatal accidents in the US mining industry using the data collected from MSHA from 1995 to 2006. In the hazard identification stage, the authors identified ten hazards for each loader and dozer operations. The authors used a quantified risk matrix to analyse the risk level of the identified hazards. The results concluded that the hazards: failure to follow adequate maintenance procedure and failure of mechanical/electrical/hydraulic components were the most severe and frequent hazards for the loaders and the hazard: failure to identify adverse site/ geological conditions was the most severe and frequent hazard for the dozers.

Grayson et al. (2009) studied the violation of standards data in 31 US mines and identified the major hazards related to fires and explosions in mines. The identified hazards in different mines were analysed using quantitative risk matrix. The authors evaluated the risk level as the product of the frequency of occurrence of citations and cost of citation violation.

Orsulak et al. (2010) analysed the risks associated with the safety violation in US underground coal mines using quantitative risk matrix. In this study, the authors classified the consequence based on penalties received per year by mines and the frequency based on the number of citations received per year.

Jiang et al. (2012) analysed roof fall accidents in coal mines using FTA and identified failure to support, improper geological conditions, roof suspension and lack of awareness of safety measures among leaders and workers as the most important basic events that can cause roof fall accident.

Shao-jie (2013) analysed the coal mine fire accidents using FTA and identified the root causes as follows: electrical equipment catching fire, the blaze caused by man, explosive blaze and coal ignition.

Kumar and Ghosh (2017) attempted to explore the top and initiating events of the methane explosion in underground mines using integrated event tree and FTA. Electric spark and cutter pick spark were the top events identified using event tree. Degraded fan performance, turned off fan, use of scavenger system with inadequate overlap, ventilation duct is set far from face, leak in ducts, pinched ducts, welding, electrical sparks, non-explosion proof equipment design, undersized ductwork, non-availability of gas monitoring equipment and cutter pick sparks were identified as the basic events using FTA.

Domínguez et al. (2019) identified the environmental, physical, mental, and natural hazards associated with the blasting, use of machinery and equipment in underground mines. The authors attempted to analyse and assess the risks associated with blasting, use of machinery and equipment using a 4× 4-risk matrix. The results concluded that the use of machinery and equipment have medium risk and blasting operation has low risk.

2.5. Limitations of Safety Risk Analysis Techniques

2.5.1. Qualitative vs quantitative

Many authors have compared the qualitative and quantitative techniques to find the best suitable approach for the evaluation of risk in the workplace.

Pidgeon (1988) pointed out that prior knowledge of complete and accurate data on failure situations were required to conduct a probabilistic risk assessment and argued that it was not easy to get the data except for minor and well-understood situations.

Niczyporuk (1996) stated that the quantitative risk assessment yields more accurate results than qualitative risk assessment. The author also stated that the use of an arbitrary scale in qualitative risk assessment might lead to the following errors:

- Overestimation of occurrences with high consequence and low probability event,
- Underestimation of occurrences with low consequence and high probability event, and
- Output of hazards assessed by experts may have a different value.

Frosdick (1997) stated that the quantitative risk evaluation methods highly depend on the availability of data and questioned the accuracy of available data.

Raman (2003) stated that the quantitative risk assessment methods depend highly on the frequency data of initiating events of the major accidents and probability data on human error failure that was not available for the mining industry.

Joy (2004) discussed various qualitative and quantitative risk assessment techniques applied to mine operations and equipment in the Australian mining industry. The author has stated that due to lack of accurate data about hazard event likelihood and due to the availability of experienced employees at different levels, who can suggest subjective consequence and likelihood, the qualitative risk assessment was commonly preferred in the Australian mining industry.

Rasche et al. (2006) stated that quantitative models have advantages over qualitative risk ranking methods, where numerical data was available. The authors also pointed out that the mineral industry globally still lacks good developed hazard database and related risk assessment data.

Rasche and Knights (2012) pointed out the limitations of the qualitative techniques used and suggested to implement quantitative methods in the mining industry. The few limitations pointed out were the subjective judgement, peoples' inexperience, perceptions and assumptions particularly in a time of skill shortage. The authors illustrated how the other high-risk industries had applied quantitative techniques and improved safety, and operational performance. The authors also stressed the need to develop a quantitative database and to improve training in the mining industry.

Curtis and Carey (2012), Ramona (2011) presented the advantages and disadvantages of qualitative and quantitative approaches in Table 2.4.

Table 2.4 Advantages and disadvantages of qualitative and quantitative methods

Methods	Advantages	Disadvantages
Qualitative	• Easy to understand and observe the level of risk. • Easy to understand and implement the methods of calculation of risk level. • Quantification of risk parameters are not required.	• This method gives subjective results. • It is possible that the reality is not being defined correctly because of the subjective perspective of the team members.

	• Accurate risk parameters data are not required.	• Hard to implement control measures due to the subjective judgement. • Insufficient differentiation between levels of risk (i.e. high, medium, low). • Results depend on the quality of risk management team members.
Quantitative	• The evaluation and the results of the risk assessment process are based on objective methods. • Risks are sorted by the numerical values obtained after evaluating the risk parameters. • The results can be expressed in a specific management terminology.	• The methods of calculation of risk level are complex. • Very difficult to implement the risk assessment process without an automatic tool. • Results depend on the availability of risk parameters data. • Hard to understand the results for inexperienced people. • The values of risk impacts are based on the subjective opinions of the people involved. • Takes a long time to complete the risk assessment process.

2.5.2. Safety risk analysis techniques

Informal risk analysis techniques, i.e. WRAC, FMEA, FTA, and ETA are the most commonly applied to mining operations and equipment in the Australian mining industry (Joy, 2004; Joy & Griffiths, 2007). For evaluating the risk level, both WRAC and FMEA methods are dependent on either rapid ranking method or risk matrix.

The rapid ranking method is the most commonly adopted technique in the global mining industry (DGMS, 2002; Iannacchione et al., 2008; SIMTARS, 2001; Tripathy & Patra, 1998). The process of this method is a basic multiplication of three criteria: probability, exposure, and consequence. Though the process of this method is same in all countries, the scales of the three criteria may vary from one country to another, as they are outlined as per the requirement of the country's mining industry. However, the output obtained is crisp in nature, as the crisp inputs based on the scales used. Because of the crisp nature of the output, it has been criticised by many authors. Some of the significant shortcomings were listed as follows:

- Different values of probability, exposure, and consequence ratings may produce the same value of Risk Priority Number, but their hidden risk implications may be very different. For example, two different events with values of 3, 2, 2 and 1, 3, 4 for probability, exposure, and consequence respectively, will have the same RPN value of 12 (Bowles & Peláez, 1995; Oraee et al., 2011; Shariati, 2014; Dallat et al., 2017).

- The relative importance among probability, exposure, and consequence was not taken into consideration. The three factors were assumed to have equal importance. This may not be the case when considering practical application of WRAC or FMEA (Bowles & Peláez, 1995; Oraee et al., 2011; Shariati, 2014; Dallat et al., 2017; Gul et al., 2017).
- The inputs of the three factors were difficult to determine precisely. Much information in WRAC or FMEA can be expressed in a linguistic way such as high, medium and so on (Bowles & Peláez, 1995; Oraee et al., 2011; Shariati, 2014; Dallat et al., 2017).

Băbuţ et al. (2011) stated that the quality of the assessment of this method depends on the experts' team and was a subjective method, which gives a false safety feeling. Verma and Gupta (2013) pointed out that the computational complexity and time required in calculating risk level, data unavailability or uncertainty were the disadvantages of the rapid ranking method. Verma and Chaudhari (2016b) indicated that the output of this method might contain vagueness as this method was based on the perception of experts participating in the process.

The risk matrix is used to rank different risks in order of importance. Probability or frequency and consequence or likelihood were used on the two axes of the risk matrix, and the output will be categorised into three or more groups like low, medium or high. The use of the risk matrix was promoted in Indian (DGMS, 2014a), American (Iannacchione et al., 2008) and Australian mines (AS/NZS, 2004). The main limitations of the risk matrix were:

- Ranking of the evaluated risks was limited to the pre-defined categories only. For example, the result obtained in Ghosh (2010) study showed that out of ten causes evaluated, 1 cause has low risk level, 1 has minor risk level, 2 has medium risk levels, and 6 has major risk levels. It was hard to rank further among the six causes with major risk level.
- The crisp risk scores assigned to likelihood and severity in the risk matrix lead to uncertainty in the risk assessment process (Iphar & Cukurluoz, 2018).

FTA is commonly adopted to identify the root causes of an accident in mines while ETA is adopted to analyse the control measures to be employed to mitigate the consequence.

Bow-tie method is a combination of FTA and ETA. Lee et al. (1985) and Marhavilas et al. (2011) stated that the time required, cost of development of FTA for a system will be very high, it is more suitable for a complex system and it may not reveal all the underlying causes. Marhavilas et al. (2011) termed the ETA as a time consuming, expensive and very complicated application.

Pillay (2015) and Escande et al. (2016) pointed out that the current risk assessment techniques used in safety management were outdated and suggested using the existing techniques in new and innovative ways. Citing the pros and cons of the risk analysis techniques, many researchers have applied soft computing techniques either alone or along with Multi Criteria Decision Making (MCDM) techniques to evaluate the risks in the underground coal mines.

Bowles and Peláez (1995) point out that the problems in analysing the results obtained by FMECA method and suggested the application of fuzzy logic method to FMECA as a solution to overcome the problems.

Fera and Macchiaroli (2009, 2010) stated that the qualitative techniques were too simple and subjective, and quantitative techniques were too complex to implement. Therefore, the authors proposed the application of a semi-quantitative technique for improving safety. The proposed methodology consists of FMECA, the Scenario-Based Risk Assessment, Italian standard on Statistics on Occupational Injuries and AHP. The authors used the Scenario-Based Risk Assessment method to identify the major risk events, FMECA to calculate the criticality of risks, Italian standard on Statistics on Occupational Injuries to calculate the frequency and occurrence and AHP to reduce the subjectivity in experts' opinion.

Oraee et al. (2011) cited the important criticisms on FMEA method and applied fuzzy FMEA to evaluate safety hazards in an underground coal mine. The fuzzy FMEA results showed that rock burst was the most hazardous parameter followed by the roof collapse.

Mahdevari et al. (2014) attempted to assess safety risks in underground coal mines using fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. The authors validated the proposed method using the data collected from three coal mines. The authors identified 86 hazards from the collected data and divided them into personal, chemical, geochemical, geomechanical, electrical, environmental, social, cultural, managerial, and mechanical risks groups. The results concluded that struck by materials, instability of coal face, instability of immediate roof, firedamp, emission of gases, dealing with misfire, stopping of ventilation system, wagon separation in inclines, suffocation due to inspiration of coal dust and toxic gases, inadequate training, and poor site management system were the major hazards with high risk in the mines.

Verma and Gupta (2013) proposed fuzzy logic as a solution to overcome the problems mentioned above. By comparing the outputs of the proposed fuzzy reasoning approach with the rapid ranking method, the authors demonstrated that fuzzy reasoning approach method was capable of predicting the risk values similar to the rapid ranking method.

Petrović et al. (2014) evaluated the belt conveyor elements failure in an underground coal mine using the fuzzy logic method. The results concluded that the application of fuzzy logic theory provides a comprehensive portrait of the tendency of failure and it was easier to express the risk as a linguistic term rather than to present the risk as a numerical value. The case study results showed that the electric motor and the gearbox had the highest risk levels in the belt conveyor system.

Shariati (2014) criticised the crisp risk priority numbers used in FMEA and suggested using fuzzy FMEA in case of uncertainty. The application of fuzzy FMEA in underground mine results showed that the rock collapse was the most hazardous parameter in safety criteria, water pollution was the most hazardous parameter in environmental criteria and dust was the most hazardous parameter in health criteria.

Verma and Chaudhari (2014) proposed a fuzzy AHP methodology for analysis of risks in the mining industry. The authors have reviewed the mine accidents data from 1995 to 2012 and identified eight hazards factors. The authors evaluated the ranking of the identified hazard factors using Fuzzy AHP.

Verma and Chaudhari (2016a) stated that the statistical analysis, various distribution models and risk assessment techniques were dependent on the availability of accident data and proposed a fuzzy logic model to assess the workers' safety in mines.

Javadi et al. (2017) proposed a new methodology to evaluate the risks in underground coal mines. The proposed methodology was a combination of fuzzy TOPSIS and Bayesian networks. The authors applied the Fuzzy TOPSIS method to rank the identified hazards and Bayesian network model to quantify the roof fall risks. The hazards identified in the case study mine were roof fall, gate fall, gas explosion, dust explosion, sudden gas emission, subsidence, coal bump, and coal fire. The important factors affecting the roof fall during longwall mining were geological conditions, layer characteristics, extraction method and equipment and stress conditions.

Gul et al. (2017) addressed one of the limitations in the Fine-Kinney method, i.e. providing equal weight to all risk parameters. The authors used the combined Buckley's fuzzy AHP and fuzzy VIKOR methods to obtain weights for the risk parameters of the Fine-Kinney method and to rank hazard events.

Samantra et al. (2017) stated that the subjective judgement was easy, practical, and provides a better assessment of risk than objective analysis, as it does not depend on historical data. The authors also mentioned that the subjective information depends on experts' experience, uncertainty, and vagueness due to human intuitive assessment. To overcome the problems in qualitative and quantitative methodologies, the authors have proposed a new methodology for selection appropriate safety measure system for the underground mining industry. The proposed method was the combination of aggregative fuzzy risk analysis and modified TOPSIS.

Shi et al. (2017) attempted to assess the methane gas explosion in underground coal mines using Improved AHP. A fault tree was used to find the root causes of the methane explosion and an AHP model was constructed based on it. The results presented the ranking of ignition source of methane gas explosion as electric spark followed by blasting, welding, friction spark, smoking and smouldering.

Gul and Ak (2018) proposed a new methodology to overcome the problems in qualitative and quantitative methodologies. The methodology was a combination of 5×5-risk matrix, fuzzy TOPSIS and Pythagorean fuzzy AHP. In this study, the authors collected the data using subjective judgement, as it was easy to use and practical than objective analysis.

Iphar and Cukurluoz (2018) stated that the crisp risk scores assigned to likelihood and severity in the risk matrix lead to uncertainty in the risk assessment process and proposed to develop a fuzzy logic method to eliminate the drawbacks. In this study, 43 potential hazards of four underground coal mines in Turkey were identified, the risk parameters data of the identified hazards were collected using a developed questionnaire, and the identified risks were evaluated using the developed Mamdani fuzzy model.

2.6. Status of Safety Risk Management in the Mining Industry

The success of risk management for effectively controlling the risks in various hazardous industries have encouraged the mining industry to adopt it.

Foster et al. (1998) acknowledged the importance of risk assessment application for improving safety performance in mines. The authors have also presented the basic elements, brief history around the world, the need for risk assessment and risk management. The case study results revealed two differences between the risk assessment process and other approaches adopted in mining. The differences were identified in the estimation of risk, and the examination and documentation of control measures.

Rasche (2001a) suggested risk assessment tools to frame preventive safety and maintenance strategies in mines. The author also suggested selecting risk assessment tool based on the type of hazard present and the ability of the tool.

Sahu and Pal (2000) stated that the accident statistics in the Indian mining industry were not adequate to perform a detailed study and suggested adopting risk assessment as a method to assess the safety risks in mines.

Xin-chun and Xue-feng (2009) stated that the application of safety risk management system in coal mines would help achieving safe production, minimize the risks and prevent accidents in an effective, systematic and scientific ways.

Dash et al. (2015) suggested using risk assessment to find the root causes and implement corrective measures in Indian underground coal mines.

Dash et al. (2016) stated that it was essential for the Indian mining industry to adopt risk assessment to identify hazards and ensure proper control measures.

2.6.1. Legislative provisions in India and abroad

During the past few years, the legislative requirement for risk assessment and risk management have been increasing in almost every industry. The legislative requirements are important especially in the mining industry, as mining can never have zero risks due to the inherent hazards associated within. Therefore, many countries have framed risk management guidelines as per their requirements to manage safety risks in the mining industry.

Australia is the first country to frame guideline based on risk management. The Chief Inspector of coal mines in New South Wales has published a risk management handbook for the mining industry (NSWDPI, 1997) that presents a variety of procedures to assess and manage risks, which was later revised in 2011 (NSWDTI, 2011). The New South Wales also published a Safety Management Systems in Mines guidelines in 2014 (NSWDTI, 2014). Queensland published its standards in 1998 and 1999 (QDME, 1998; QMC, 1999). In Western Australia, the application of risk management processes gained popularity in 2003 (CMEWA, 2003). The Mineral Industry Safety and Health Centre at University of Queensland developed the National Minerals Industry Safety and Health Risk Assessment Guidelines (Joy & Griffiths, 2007) which outlines a risk management framework, and is widely used in the Australian mining industry. At the same time, they also launched online interactive tools RISKGATE (Kirsch et al., 2014) and MIRMGate (Kizil & Joy, 2005) for assessing risk controls and hazard-related information respectively. Systematic and comprehensive risk management was recommended to be employed in all the mines to improve the safety in underground coal mines in the US mining industry (Iannacchione et al., 2008).

The health and safety management structure, instructions, rules, and schemes applicable to UK mining industry were pointed out in the Mines Regulation, 2014 (HSE, 2014). The Mines Regulation, 2014 has replaced all the previous mine specific health and safety legislation. Risk assessment guidelines for mines in Alberta, Canada, were published in Occupational Health and Safety regulations (GOA, 2003) and Occupational Health and Safety code (GOA, 2009). The South African mining industry initiated a Hazard Identification and Risk Assessment programme for systematic identification and documentation of risks (HIRA, 2003). ILO has released a draft code of practice on safety and health in underground coal mines in 2006 and a final version in 2009 (ILO, 2009).

A tripartite forum at Ninth, Tenth and Eleventh Conference on Safety in Mines held at New Delhi on February 2-3, 2000, November 26-27, 2007, and July 5-4, 2013 respectively, recommended for commencing a formal risk assessment process in the Indian mining industry (DGMS, 2000, 2007, 2013). DGMS had circulated, guidelines for implementation of Safety Management System (SMS) in 2002 (DGMS, 2002), plan for audit and review of SMS in 2011 (DGMS, 2011), promoted risk calculator (DGMS, 2014a) and Take5 (DGMS, 2014b) approaches in 2014, an integrated approach for the development of Safety Management Plan (SMP) for coal and metalliferous mines in 2016 (DGMS, 2016).

Performing SMP in mines was made mandatory after the revision of the Coal Mines Regulations in 2017 under section 37 and 104 (Ministry of Labour and Employment, 2017). The below sections briefly presents the details of the section 37 and 104 of the Coal Mines Regulations 2017.

2.6.1.1. Section 37: Duties and responsibilities of owner

1. In taking preventive and protective measures, the owner shall arrange for regular assessment of the risk and dealing with it in the following order of priority:
    a. eliminate the risk;
    b. control the risk at source;
    c. minimize the risk that include the design of safe work systems; and
    d. in so far as the risk remains, provide for the use of personal protective equipment, having regard to what is reasonable, practicable and feasible, and to good practice and the exercise of due diligence.
2. Owners shall take all necessary measures to eliminate or minimize the risks to safety and health of persons employed in mines under their control and shall:
    a. ensure that the mine is designed, constructed and provided with electrical, mechanical and other equipment, including a communication system, to provide conditions for safe operation and a healthy working environment;
    b. ensure that the machine is commissioned, operated, maintained and de-commissioned in such a way that workers can perform the work assigned to them without endangering their safety and health or that of other persons;
    c. take steps to maintain the stability of the ground in which persons have access in the context of their work;
    d. where practicable, provide from every underground workplace, two exits each of which is connected to separate means of egress to the surface;
    e. ensure the monitoring, assessment and regular inspection of the working environment to identify the various hazards to which the workers may be exposed and to assess their level of exposure;
    f. ensure adequate ventilation for all underground working to which access is permitted;
    g. in respect of zones susceptible to particular hazards, draw up and implement an operating plan and procedures to ensure a safe system of work and the protection of workers;

h. take measures and precautions appropriate to the nature of a mine operation to prevent, detect and combat the start and spread of fires, explosions and inundations;
i. ensure that, when there is serious danger to the safety and health of workers, operations are stopped and workers are evacuated to a safe location;
j. ensure that corrective actions are taken immediately, when manager or other officials report non-compliance with safety and health regulations or code of practice by any person.

3. The owner shall ensure preparation of an emergency response plan specific to each mine for reasonably foreseeable industrial and natural disasters.
4. Where workers are exposed to physical, chemical or biological hazards, the owner shall:
   a. inform the workers, in a comprehensible manner, of the hazards associated with their work, the health risks involved and relevant preventive and protective measures;
   b. take appropriate measures to eliminate or minimize the risks resulting from exposure to those hazards;
   c. where adequate protection against risks of accident or injury to health including exposure to adverse conditions is not possible to be ensured by other means, provide and maintain at no cost to the worker, suitable protective equipment, clothing as necessary and other facilities as defined by these regulations;
   d. provide workers who have suffered from an injury or illness at the workplace with first aid, appropriate transportation from the workplace and access to appropriate medical facilities.
5. The owner shall ensure that:
   a. adequate training and re-training programs and comprehensible instructions are provided for workers, at no cost to them, on safety and health matters as well as on the work assigned;
   b. adequate supervision and control are provided in each shift to secure the safe operation of the mine;
   c. a system is established so that the names of all persons who are employed belowground can be accurately known at any time, as well as their probable location;

   d. all accidents and dangerous occurrences are investigated and appropriate remedial actions are taken;

6. The owner shall ensure regular health surveillance of workers exposed to occupational health hazards specific to mining operations.

2.6.1.2. Section 104: Safety management plan

1. The owner, agent and manager of every mine shall:
   a. identify the hazards to health and safety of the persons employed at the mine to which they may be exposed while at work;
   b. assess the risks to health and safety to which employees may be exposed while they are at work;
   c. record the significant hazards identified and risks assessed;
   d. make those records available for inspection by the employees; and
   e. follow an appropriate process for identification of the hazards and assessment of risks.
2. The owner, agent and manager of every mine, after consulting the safety committee of the mine and Internal Safety Organisation, shall determine all measures necessary to:
   a. eliminate any recorded risk;
   b. control the risk at source;
   c. minimise the risk; and
   d. in so far as the risk remains,
      - provide for personal protective equipment; and
      - institute a program to monitor the risk to which employees may be exposed.
3. Based on the identified hazards and risks, the owner, agent and manager of every mine shall prepare an auditable document called "Safety Management Plan", that forms part of the overall management and includes organisational structure, planning, activities, responsibilities, practices, procedures, processes and resources for developing, implementing, achieving, reviewing and maintaining a safety and health policy of a company.
4. It shall be the duty of the owner, agent and manager to implement the measures determined necessary and contained in the SMP for achieving the objectives set out in sub-regulation (2) in the order in which the measures are listed in the said sub-regulation.

5. The SMP shall contain:
   a. defined mine safety and health policy of the company;
   b. a plan to implement the policy;
   c. how the mine or mines intend to develop capabilities to achieve the policy;
   d. principal hazard management plans;
   e. standard operating procedures;
   f. ways to measure, monitor and evaluate performance of the SMP and to correct matters that do not conform with the SMP;
   g. a plan to regularly review and continually improve the SMP;
   h. a plan to review the SMP if significant changes occur; and
   i. details of involvement of mine workers in its development and application.
6. The owner, agent and manager of every mine shall periodically review the hazards identified and risks assessed, to determine whether further elimination, control and minimisation of risk is possible and consult with the safety committee on review.
7. The owner, agent or manager of every mine shall submit a copy of the SMP to the Regional Inspector who may, at any time by an order in writing, require such modifications in the plan as he may specify therein.
8. The owner, agent and manager of every mine shall be responsible for effective implementation of the SMP.

2.7. Critical Review

The hazard factors and hazard events that affect the safety in underground coal mines were identified from the literature review. The outline of identified hazard factors from the literature is shown in Table 2.5. The hazard factors that affected the safety in Indian underground coal mines were roof fall and side fall; conveyor; haulage; machinery; explosives/blasting; electricity; dust, gas and combustible materials; and inundation.

Table 2.5 Hazard sources identified

Causes	References
Roof fall and side fall	Mandal and Sengupta (2000), Donoghue (2004), Padhi (2004), Burgess-Limerick and Steiner (2007), Iannacchione et al. (2008), Asia Monitor Resource Centre (2010), Kunar et al. (2010), Khanzode et al. (2011a), Bhattacherjee et al. (2011), Kunar et al. (2008), Dash et al. (2017), Zhang et al. (2018), Selçuk et al. (2000), Chen et al. (2012), Tripathy and Patra (1998)
Conveyor	Mandal and Sengupta (2000)
Haulage	Mandal and Sengupta (2000), Padhi (2004), Iannacchione et al. (2008), Asia Monitor Resource Centre (2010), Bhattacherjee et al. (2011), Kunar et al. (2008), Zhang et al. (2018), Selçuk et al. (2000), Chen et al. (2012), Tripathy and Patra (1998)

Machinery	Leigh et al. (1990), Donoghue (2004), Burgess-Limerick and Steiner (2007), Iannacchione et al. (2008), Asia Monitor Resource Centre (2010), Khanzode et al. (2011a), Bhattacherjee et al. (2011), Kunar et al. (2008), Zhang et al. (2018), Selçuk et al. (2000), Tripathy and Patra (1998)
Explosives/blasting	Mandal and Sengupta (2000), Bhattacherjee et al. (2011), Kunar et al. (2008), Chen et al. (2012)
Electricity	Mandal and Sengupta (2000), Donoghue (2004), Asia Monitor Resource Centre (2010), Zhang et al. (2018), Selçuk et al. (2000), Tripathy and Patra (1998)
Dust, gas and other combustible materials	Mandal and Sengupta (2000), Singh and Sen (2001), Donoghue (2004), Asia Monitor Resource Centre (2010), Dash et al. (2017), Zhang et al. (2018), Selçuk et al. (2000), Chen et al. (2012), Tripathy and Patra (1998)
Fall of persons	Iannacchione et al. (2008), Selçuk et al. (2000)
Inundation	Mandal and Sengupta (2000), Donoghue (2004), Dash et al. (2017), Zhang et al. (2018), Selçuk et al. (2000), Chen et al. (2012), Tripathy and Patra (1998)

The identified hazard factors/causes were just secondary events, which were caused by other events and therefore, every cause identified should be further investigated in-detail (Mandal & Sengupta, 2000). However, such attempts to analyse hazard events were scarce and limited literature was found on roof fall and side fall, conveyor, electricity, machinery, dust, gas and other combustible materials, and inundation. Therefore, all the hazard factors/causes need to be investigated for identifying the hazardous events.

Although various countries have framed guidelines for carrying out the risk assessment process in the mining industry, the type of risk analysis techniques suitable for evaluating various mining scenarios were not stated. DGMS (2002) recommended adopting the rapid ranking method in the Indian mining industry and it was assumed that this approach would evaluate all kinds of risks present in mines. It remains only wishful thinking since different tools have different purposes and give different output. This necessitates a need for trying different risk analysis techniques for evaluating risk in Indian mines. The qualitative techniques identified from the literature were risk matrix, rapid ranking method, WRAC, FMEA, FTA, ETA, bow-tie methods and the quantitative techniques were FTA, ETA, and risk matrix. It was also observed that the research studies on risk analysis techniques in Indian underground coal mines were very limited to either statistical analysis of accidents or study of single equipment or operation using qualitative and quantitative techniques. Limited work has been done to identify, analyse, and evaluate the safety risks of an overall underground coal mine in India.

The study of risk analysis techniques revealed that assessment of risk could be conducted by using either qualitative or quantitative techniques. Qualitative risk analysis techniques like risk matrix, rapid ranking method, WRAC, and FMEA are easy to execute and practical as they are not dependent on the historical data; rather they need experience and close examination. However, the qualitative risk assessment techniques may yield subjective results due to instinctive human assessment. Quantitative risk assessment techniques like FTA and ETA are substantially dependent on the accuracy of available data. However, in many situations, these methods fail to deal well with uncertain or incomplete data. Therefore, it may be very hard to conduct a quantitative risk assessment in the Indian mining industry, where only the number of accidents occurred are recorded. The consequence and the exposure data remains unrecorded or unavailable. Therefore, a new methodology is needed to be developed for risk assessment in underground coal mines to effectively assess the safety risks. The proposed methodology should be able to address the limitations of risk analysis techniques like uncertain input data, the relative importance of risk parameters, computational complexity, time, and ranking.

In this study, the identified hazard factors of the Indian underground coal mines were examined to identify and assess the associated hazard events using WRAC, FMEA, FTA and ETA. Due to the limitations of these approaches as presented in Section 2.5.2, a new methodology to evaluate safety risk assessment for underground coal mines was proposed. In the proposed methodology, the relative importance of probability, exposure and consequence were taken into consideration; the data was collected using the linguistic scales; and analysis was done using the amalgamation of Mamdani fuzzy logic approach, VIKOR, and AHP techniques to overcome the uncertainty and ranking issues.

2.8. Chapter Summary

In this chapter, an extensive review of the literature on hazard identification, risk analysis, risk assessment, risk management in underground coal mines is presented. The hazard sources that affect the safety in underground coal mines were identified. The advantages and disadvantages of the qualitative and quantitative risk analysis techniques were discussed briefly. Based on the literature review, research problems were identified and presented in the critical review section.

CHAPTER 3

RESEARCH METHODOLOGY

3.1. Introduction

Evaluation of safety risks is a complex process of identifying and assessing the hazard factors contributing to the occurrence of accidents in underground coal mines. There are several types of hazard factors responsible for the occurrence of accidents in mines. Kunar et al. (2010) categorised the hazard factors as individual and occupational factors. The occupational hazard factors identified in underground coal mines are ground movement, rope haulage system, belt conveyor system, LHD, shot firing and blasting, electricity, dust, gas and other combustible material, and inundation. Individual hazard factors namely life-style, health, demographic, socio-economic, and behaviour related factors were not considered in this study.

In mines, any working operation involves the interaction of people, machines, and environment within procedural constraints (Bullock, 1979; Hammer, 1972; NSWDTI, 2011). Therefore, it is requisite to identify human, safe work procedures/practices, work environment, and equipment related hazards and their interactions to develop a comprehensive list of hazards in the workplace. There are various risk assessment techniques available for evaluation of risk (Arunraj & Maiti, 2007; Tripathy, 2014; Xue et al., 2010). The risk assessment techniques identified from the literature viz. WRAC, FMEA, FTA, ETA are used in this thesis for hazard identification, risk analysis and risk evaluation.

The comprehensive methodology developed in this thesis is shown in Figure 3.1. In this chapter, the steps involved in developing a research methodology for evaluating safety risks in underground coal mines are presented. This includes the overview of qualitative and quantitative approaches, and outline of the proposed methodology to assess and rank the safety risk level of the hazardous events, hazard groups, and overall underground mine. The details of the study area and the application of the comprehensive methodology developed is also presented in this chapter.

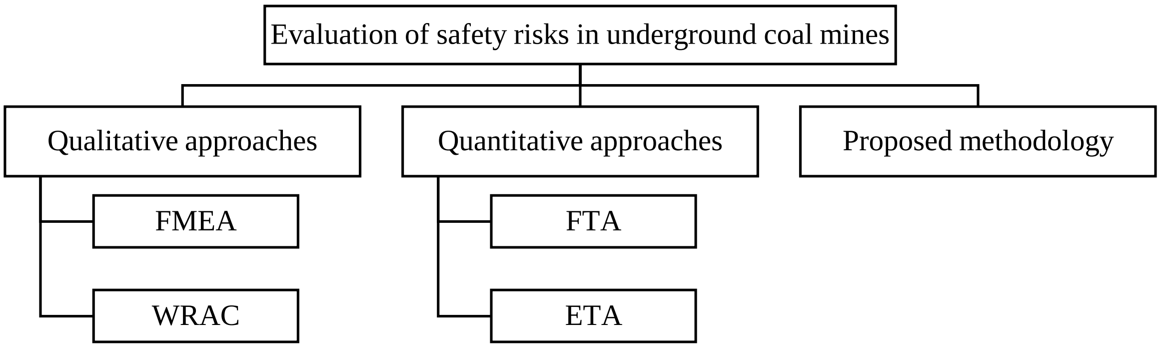


Figure 3.1 The research methodology

3.2. Qualitative Approaches

3.2.1. Failure Mode and Effects Analysis

FMEA is a highly structured and systematic technique for identifying all the possible failures in a machine, design, or assembly process (Mannan, 2012; MIL-STD, 1980). "Failure mode" means the ways in which something might fail. "Effect analysis" refers to studying the consequences of those failures. FMEA is more suitable to identify hazards related to machine design changes. The FMEA technique is generally used to assess risk qualitatively or semi-qualitatively. It can be used for assessing risk quantitatively using actual failure rates. The commonly used method to evaluate the risk quantitatively is shown in equation 3.1.

$$Risk\ Priority\ Number\ (RPN) = S\ * O * D \tag{3.1}$$

Where, S = Severity of the failure

O = likelihood of occurrence of the failure

D = likelihood of the not detecting the failure

Other less common techniques like risk matrix, past experience, process maps can also be used to evaluate risks in FMEA. The rapid ranking method recommended by DGMS (2002) uses equation 2.1 for evaluation of risk and the scales of risk parameters are shown in Table 3.1. The scales of risk parameters were presented by DGMS (2002) for conducting risk assessment process in the Indian coal mines. For evaluation of risk using rapid ranking method, the expert selects a hazard and assess the level of consequence, exposure, and probability of the hazard. For example, if the selected hazard has consequence of "several dead", then the expert selects rank 5 from Table 3.1. Similarly, if the selected hazard has exposure of "very rare" and probability of "quite possible", then the expert selects 1.5 and 7 respectively from Table 3.1. Using the equation 2.1, risk score can be calculated as 52.5 (5 *1.5 *7). In the same way, the process is repeated for all the hazards present for evaluation of risk score. Based on the risk scores of the evaluated hazards, appropriate risk treatment techniques are applied to mitigate or eliminate the risks. The procedural steps involved in the conducting FMEA are shown in Figure 3.2.

The advantages of the FMEA technique are as follows:

- Identify potential failure modes, their causes and consequences;
- Application ranges widely from the system, equipment failure modes to procedures and software;
- Presents output in an easily readable format;
- Provide input data for developing FTA.

Table 3.1 Scales of risk parameters

Consequence	Rank	Exposure	Rank	Probability	Rank
Several dead	5	Continuous	10	May well be expected	10
One death	1	Frequent (daily happening)	5	Quite possible	7
Significant chance of fatality	0.3	Seldom (weekly)	3	Unusual but possible	3
One permanent disability / least chance of fatality / serious accident	0.1	Unusual (may be once a month)	2.5	Only remotely possible	2
Many minor injuries / lost time injuries	0.01	Occasionally (yearly)	2	Conceivable but unlikely	1
One minor injury	0.001	Very rare (once in 5 years)	1.5	Practically impossible	0.5
No time loss injury	0.0001	Once in 10 years	0.5	Virtually impossible	0.1
		Once in 100 years	0.02		
		Never in the world in any industry	0.01		

3.2.2. Workplace Risk Assessment and Control

From the early-90s', WRAC is the most commonly employed technique in the Australian mining industry for evaluating risks. The application of the WRAC technique in the Australian mining industry has shown a sharp improvement in the areas of safety. WRAC is a participative risk ranking approach that allows the analyst to concentrate on the highest risk. It is a powerful tool for identifying potential production and operational losses (Iannacchione et al., 2008; Joy & Griffiths, 2007).

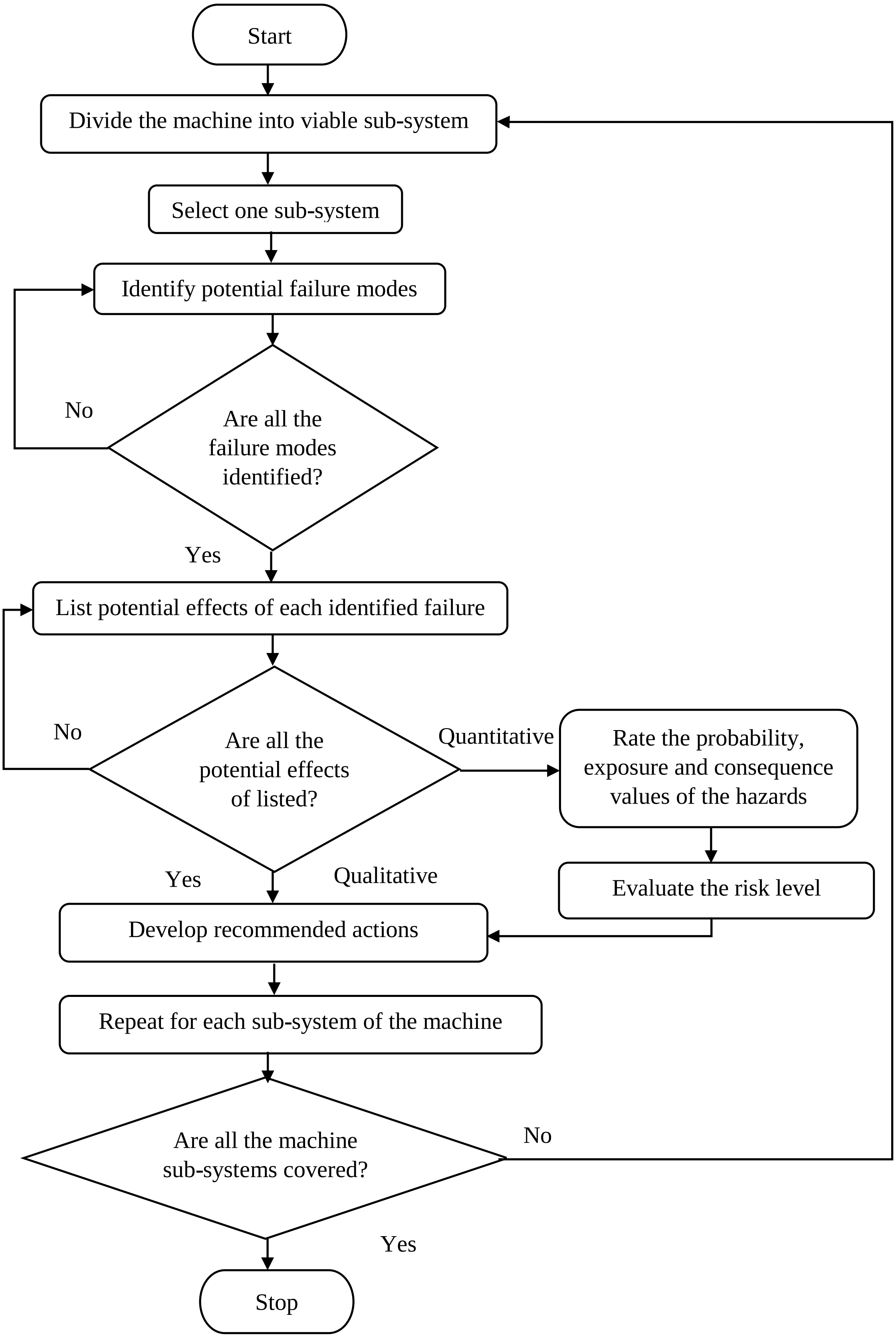


Figure 3.2 Flowchart for conducting FMEA study

Before starting a WRAC study, a clear objective, scope of the system, types of hazards to be considered, depth of the analysis, and risk scoring details should be established. The procedural steps involved in the conducting WRAC are shown in Figure 3.3. The WRAC technique is generally used to assess risk qualitatively or semi-qualitatively. It can be used for assessing risk quantitatively using actual failure rates. Rapid ranking method and risk matrix are commonly used to evaluate risks in WRAC tool. The output of the WRAC tool is a list of current, planned or potential new controls to mitigate priority risks (Thompson, 1999). The advantages of the WRAC technique are:

- It is suitable for identifying multiple failures in the system;
- Unlike FMEA, its study is not limited to only failure modes, but to the elements that comprise the integration of human, machinery, and environment;
- Can be applied in any stage of the process;
- Can be applied to identify all type of hazards like electrical, mechanical, and gravitational.

The 5×5-risk matrix exercised in CIL is shown in Table 3.2 (Sabir et al., 2012). The description of the likelihood and consequence scales are presented in Table 3.3.

Table 3.2 5×5-Risk matrix

Risk		Consequence				
		Insignificant (C_1)	Minor (C_2)	Moderate (C_3)	Major (C_4)	Catastrophic (C_5)
Likelihood	Rare (L_1)	1	3	6	10	15
	Unlikely (L_2)	2	5	9	14	19
	Possible (L_3)	4	8	13	18	22
	Likely (L_4)	7	12	17	21	24
	Almost Certain (L_5)	11	16	20	23	25

Note: Risk Score:

Low: 1-6	Medium: 7-19	High: 20-25

Table 3.3 Scales for consequence and likelihood

Consequence	Safety description	Likelihood	Safety description
Insignificant (C_1)	No Treatment	Rare (L_1)	Occurs once every 1000-10000 years
Minor (C_2)	First Aid Treatment	Unlikely (L_2)	Occurs once every 100-1000 years
Moderate (C_3)	Medical Treatment	Possible (L_3)	Occurs once every 10-100 years
Major (C_4)	Extensive Injuries, Single Fatality	Likely (L_4)	Occurs once every 1-10 years
Catastrophic (C_5)	Multiple Fatalities	Almost Certain (L_5)	High frequency of occurrence, occurs once every year

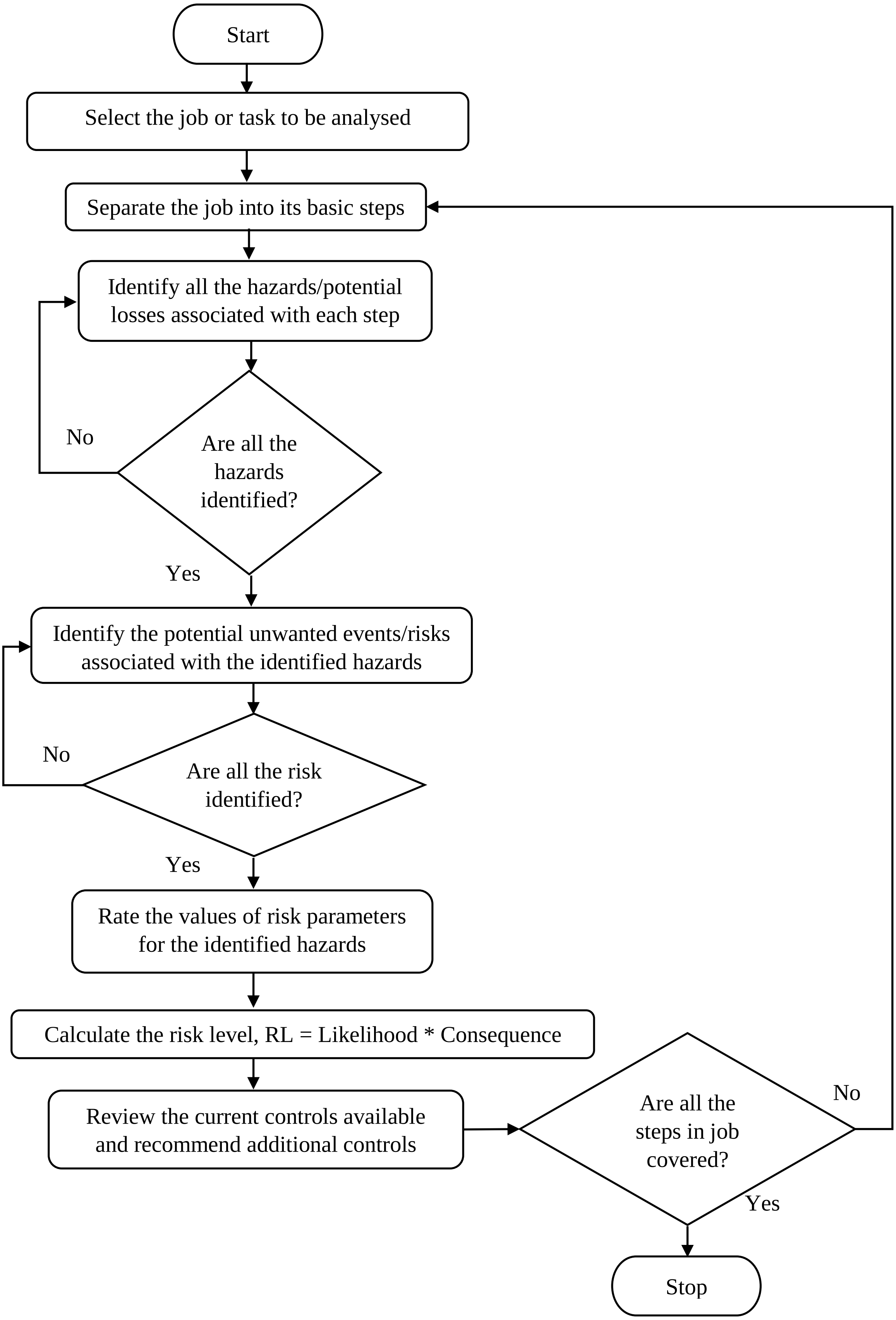


Figure 3.3. Flowchart for conducting WRAC study

3.3. Quantitative Approaches

3.3.1. Fault Tree Analysis

FTA is a top-down, deductive technique that focuses on one particular accident event and provides a method for determining the possible combination of causes of that event (Lapp & Powers, 1977). In simple terms, FTA is a risk analysis technique that helps to understand how the undesired event has occurred, to determine the failure rate of the events, and to identify the best way to reduce risk. In FTA, the logical relationships between the events and situations that lead to major undesired events are displayed graphically (NSWDPI, 1997). The general type of events and situations considered in the FTA study are human errors, equipment failures, and external events.

The steps involved in FTA for evaluating risks are shown in Figure 3.4 (Stamatelatos et al., 2002). The construction of the fault tree starts with the definition of the major undesirable (TOP) event, and intermediate events that can lead to the outcome. The fault tree should be logically progressed downwards until the basic events also called as root events are identified. The events are connected using logical connections like "AND" and "OR". The common symbols used in the construction of FTA is represented in Table 3.4.

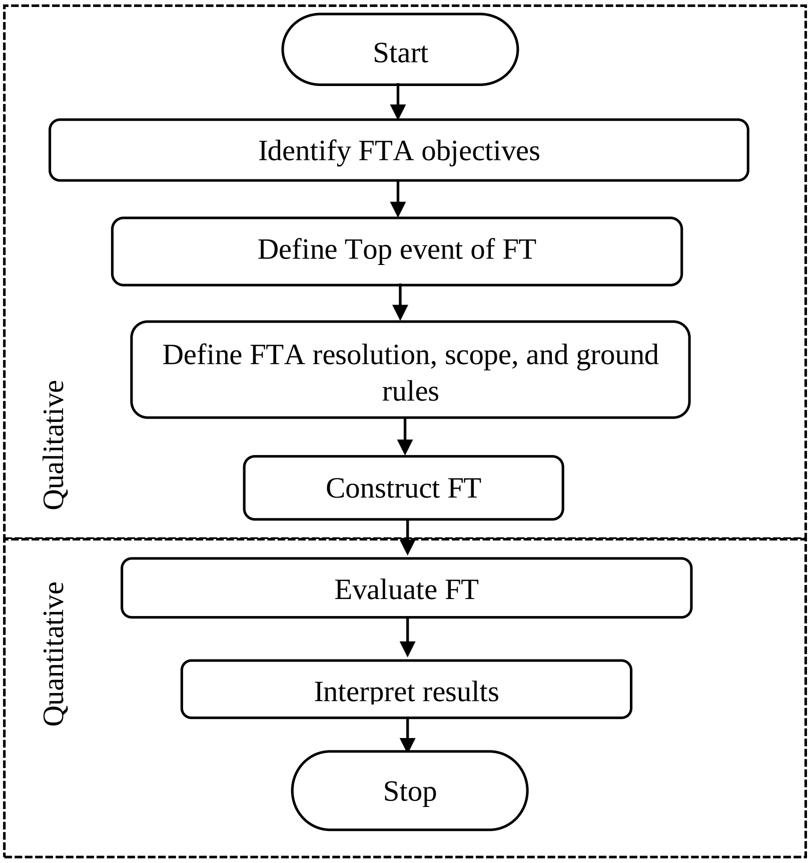
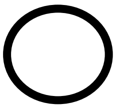
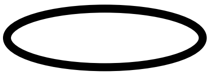
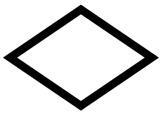
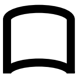
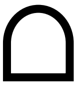
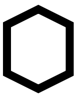
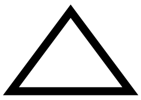


Figure 3.4. Procedure of FTA

Table 3.4 Symbols used in the construction of FTA

	EVENT	The rectangle is used to represent the TOP event and any intermediate fault events in a fault tree
	BASIC EVENT	A basic initiating fault requiring no further development
	CONDITIONAL EVENT	Specific conditions or restrictions that apply to any logic gate
	UNDEVELOPED EVENT	An event which is not further developed either because information is unavailable
	"OR" GATE	Output fault occurs if a least one of the input faults occurs
	"AND" GATE	Output fault occurs if all of the input faults occur
	"INHIBIT" GATE	Output fault occurs if the (single) input fault occurs in the presence of an enabling condition (the enabling condition is represented by a CONDITIONING EVENT drawn to the right of the gate)
	TRANSFER EVENT	Transfer symbols are used to indicate that the fault tree continues on a different page.

The basic events are the events that can be used to represent the technical failures that lead to accidents, and the intermediate events are the events that can be used to represent operator errors that may intensify technical failures. The gates of the fault trees can be used to represent several ways in which machine and human failures combine to give rise to the accident. For instance, an AND gate implies that both initial events need to occur in order to give rise to the intermediate event. Conversely, an OR gate means that either of two initial events can give rise to the intermediate event (Reniers et al., 2005).

Once constructed, the FTA provides a system for both qualitative and quantitative evaluation. The qualitative analysis takes account of the calculation of minimal cut sets. A cut set is a set of basic events that can give rise to the TOP event. A minimum cut set is the one that contains the minimum sets of events sufficient to cause the TOP event and does not contain within itself another cut set. Boolean algebraic approach is commonly used for calculation of the minimum cut set. The rules of Boolean algebra shown in Table 3.5 are used to mathematically transform the logic structure of the original fault tree into equivalent minimal cut set fault tree (Stamatelatos et al., 2002). Customarily, the symbol '·' is used to represent the logical AND gate and the symbol '+' is used to represent the logical OR gate. Quantitative FTA is based on Reliability theory, Boolean algebra, and probability theory (Ericson, 1999).

The minimal cut sets are determined by representing the fault tree as a Boolean equation. This equation is reduced using the laws of Boolean algebra as shown in Table 3.5. Based on the logical AND or logical OR gate symbols the laws of Boolean algebra are applied. This reduction involves replacement of top event with intermediate events and intermediate events with their causes. In the first step, the top event is represented in terms of intermediate events. In the next step, the intermediate events are replaced by their Boolean equivalents. This process of replacing intermediate events is continued until the Boolean representation of the fault tree contains only basic events. The final expression represents the top event in terms of basic events only. Each term is a cut set.

Table 3.5 Rules of Boolean algebra

Designation	Mathematical symbolism	Engineering symbolism
Commutative law	$X\cap Y = Y\cap X$ $X\cup Y = Y\cup X$	X.Y = Y.X X+Y = Y+X
Associative law	$X\cap(Y\cap Z) = (X\cap Y)\cap Z$ $X\cup (Y\cup Z) = (X\cup Y)\cup Z$	X. (Y.Z) = (X.Y).Z X+(Y+Z) = (X+Y)+Z
Distributive law	$X\cap(Y\cup Z) = (X\cap Y)\cup(X\cap Z)$ $X\cup(Y\cap Z) = (X\cup Y)\cap(X\cup Z)$	X.(Y+Z) = X.Y+X.Z X+(Y.Z) = (X+Y).(X+Z)
Idempotent law	$X\cap X=X$ $X\cup X=X$	X.X=X X+X=X
Law of absorption	$X\cap(X\cup Y)=X$ $X\cup(X\cap Y)=X$	X.(X+Y)=X X+X.Y=X
de Morgan's theorem	$(X\cap Y)^{l}= X^{l}\cup Y^{l}$ $(X\cup Y)^{l}= X^{l}\cap Y^{l}$	$(X.Y)^{l}= X^{l}+Y^{l}$ $(X+Y)^{l}= X^{l}.Y^{l}$

The advantages of FTA are:

- It is a highly structured method;
- It is easy to understand due to the graphical presentation;
- It can produce qualitative and quantitative results;
- It can be used as an effective root cause analysis;

- Cut set is useful in identifying the simple failure path in complex system.

3.3.2. Event Tree Analysis

Unlike FTA, ETA is an inductive approach. ETA is a forward, bottom up, logical modelling technique that uses decision trees and logically develops visual models of the range of possible outcomes of an initiating event (Diamantidis et al., 2000; Hong et al., 2009). ETA is a graphical representation of the logic model that identifies and quantifies the possible outcomes following the initiating event. In this method, an initiating event such as the failure of equipment or job is considered as the starting point, and the predictable accidental results are considered as the outcomes. The structure of ETA is developed only by including the outcomes that influence the initiating event. An event tress consists of an initiating event, probable subsequent events and final results caused by the sequence of events. Depending on the conditions at the time of the initiating event, the consequences of events vary from no injury to fatal. Probable subsequent events are independent of each other, and the specific final result depends only on the initiating event and the subsequent events following. Therefore, the occurrence probability of a specific path can be obtained by multiplying the probabilities of all subsequent events existing in a path (Marhavilas et al., 2014).

ETA is a tool that makes easy to see what pathway is creating the greatest probability of failure for a specific system. It is common to find single point failures that do not have any intervening events between the initiating event and a failure. With ETA single point failure can be targeted to include an intervening step that will reduce the overall probability of failure and thus reducing the risk of the system. The idea of adding an intervening event can happen anywhere in the system for any pathway that generates too great of a risk, the added intermediate event can reduce the probability and thus reduce the risk. The procedure for performing ETA is shown in Figure 3.5 (Clemens & Simmons, 1998; Ericson, 2005). In this study, ETA was used to determine the consequential events of the different initiating events. The advantages of ETA technique are:

- It is easy to understand due to the graphical presentation;
- It identifies both failure and success events that can cause the initiating event to occur;
- It can produce qualitative and quantitative results.

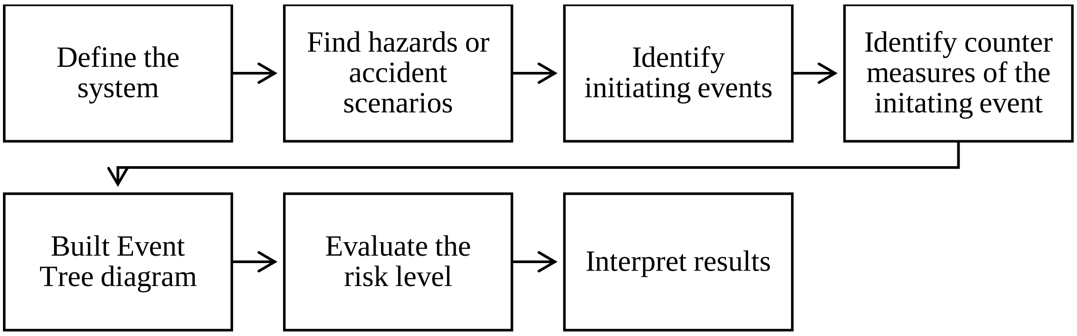


Figure 3.5 Procedure of ETA

3.4. Proposed Methodology

Along with the advantages, there are also some limitations in the employed risk analysis techniques as presented in the literature review chapter (section 2.5.2), which indicate that there is room for improvement. Therefore, a methodology was proposed in this thesis, with an aim to address the limitations of these techniques. The proposed methodology is based on unification of fuzzy logic, VIKOR, and AHP techniques.

Fuzzy logic is based on the theory of fuzzy sets, and it encompasses Artificial Intelligence, information processing and theories from logic to pure and applied mathematics, like graph theory, topology, and optimization (Pappis & Siettos, 2014). In recent years, applications of risk assessment techniques in the fuzzy logic area are increasing as this approach provides an accurate solution even when the data are approximate or uncertain. Fuzzy logic was applied for prediction of roof fall rate (Ghasemi & Ataei, 2013), to develop a novel safety diagnosis method for a coal mine production system (Wang & Zuo, 2012), for qualitative interpretation of acid mine drainage processes (Aroba et al., 2007), and for evaluating failures of belt conveyor elements (Petrović et al., 2014). All the previous applications revealed that fuzzy logic could effectively overcome the uncertainty encountered in the practical applications. Therefore, fuzzy logic was employed to evaluate the risk level of each hazard at the hazardous event level in terms of consequence, exposure, and probability.

In general, the hazards are ranked based on the evaluated risk levels, i.e. the hazard with highest risk level is considered as the highest rank, and the hazard with lowest risk level is considered as the lowest rank. If two or more hazards have equal risk level, then those hazards are given the same rank. Therefore, to ease the ranking procedure, and apply the remedial measures in an orderly manner, the VIKOR method was applied at the hazardous event level. Opricovic and Tzeng (2004) developed the VIKOR method, as a

MCDM method to solve a discrete multi-criteria problem with non-commensurable and conflicting criteria. It is aimed to determine a compromise solution for ranking and selecting considering conflicting criteria. The compromise solution is a feasible solution that is the closest to the ideal solution (Opricovic, 1998). The relative importance of the risk parameters, i.e. Probability (P), Exposure (E), and Consequence (C) is also considered in the VIKOR methodology. Mandal et al. (2015) have applied VIKOR method for ranking human errors in overhead crane operation in an opencast mine. Hayati et al. (2015) have used for determining the optimal block size in a mine.

AHP method was employed to calculate the relative importance of the hazard factors at the hazardous group level. As the contribution of each hazard to the risk of mine is different, the weight of the contribution of each hazard factor should be taken into consideration to represent its relative contribution to the risk level of the overall mine. The weights calculated using AHP indicates the degree of the relative importance of the hazard groups. AHP is one of the most popular analytical technique developed for MCDM problems. AHP aims to provide an expert with a detailed reference for decision-making and to reduce the risk of making the wrong decisions (Saaty, 1990; Wu et al., 2012). In short, it decomposes a complex decision-making problem into a system of hierarchies of objectives, criteria, and alternatives to derive ratio scales from paired comparisons. AHP can effectively deal with subjective as well as objective criteria inputs and allows some small inconsistency in judgement. The ratio scales are developed from the principle Eigenvectors, and the consistency index (C.I) is determined from the principal Eigenvalue. Kursunoglu and Onder (2015) have used AHP method for selecting an appropriate fan for an underground coal mine. Mohsen et al. (2009) have applied the AHP method for selecting an optimum underground mining method. Badri et al. (2013) have proposed using the AHP approach in risk management for underground mines.

The proposed risk assessment model has four major steps. The first step includes hazard identification; the second step involves risk quantification of identified hazards using fuzzy logic; next step consists of prioritization of hazards at event level using VIKOR method and finally prioritization of hazards at the group level and mine level using AHP technique. The illustrative flowchart of the overall methodology is represented in Figure 3.6. The details of the proposed risk assessment model are described in the following sections.

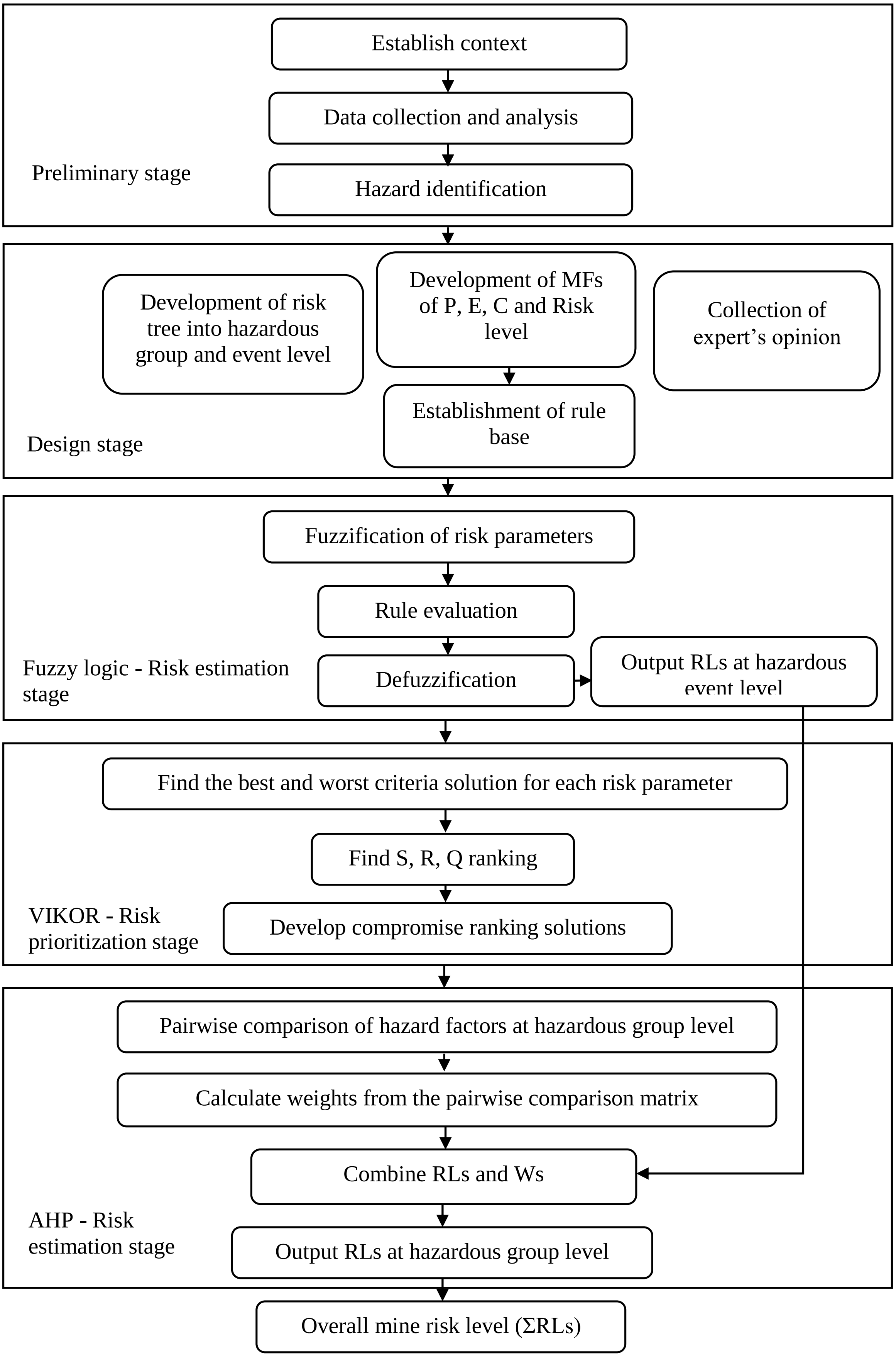


Figure 3.6 The proposed risk assessment methodology

3.4.1. Preliminary stage

The risk assessment process begins with the context establishment. Establishing the context means to define a particular task or issue, its underlying hazards and the requirement for safety at that task. Specific safety requirements of the task should be prepared at different levels, i.e. mine level, hazardous group level and hazardous event level (An et al., 2008). If the task defined in establishing the context step is indicated at the mine level, all the hazard factors of the task are categorized as hazardous group level, and the hazards related to hazard factors are considered as hazardous event level.

The next step in the risk assessment process is data collection and analysis. The goal of data collection and analysis is to gain knowledge on the types of accidents and incidents occurred in a particular mine over the years. If the statistical data are unavailable or uncertain, expert judgement should be applied, which later on will be used in the design phase to define the criteria of linguistic scales and related Membership Functions (MFs) of input risk parameters, i.e. P, E, C, and output RL.

The next step after the data collection is hazard identification. The hazard identification aims to detect all the possible hazards associated with underground coal mine methodically, i.e. identification of hazards at event level and group level after considering their effect on the overall mine safety.

3.4.2. Design stage

Once the data are collected, and hazards were identified in the preliminary stage, the risk assessment process moves from the preliminary stage to the design stage. The first job in the design stage is to develop a risk tree using identified hazards. The risk tree aims to break down the identified hazards into different levels to assess the associated risks of the underground mine effectively. The risk tree is broken down into hazardous event level, hazardous group level, and mine level as shown in Figure 3.7 (An et al., 2008). The hazardous events E_1, E_2 … E_n at hazardous event level affects the RL of hazards groups at the hazardous group level; the RLs of hazard group contribute to the overall RL of the underground mine at mine level.

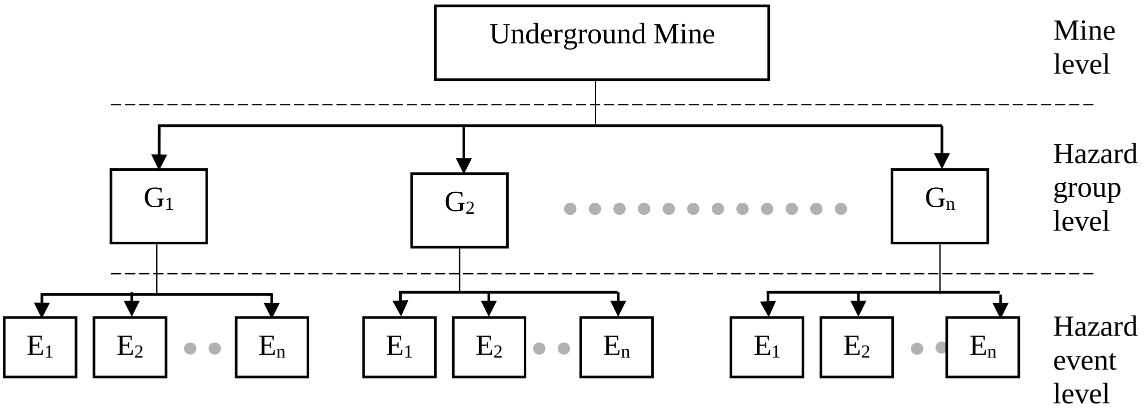


Figure 3.7 Risk tree model

The second job in the design stage is to establish the rule base. The fuzzy rule base is made up of a set of fuzzy IF-THEN statements, using experts' experience or engineering judgement (Xu, 2008). IF-THEN rules were employed to capture the imprecise modes of reasoning, which plays an essential role in the human ability to make decisions in the environments of uncertainty and imprecision. The fuzzy rules can be developed from engineering judgement, experts' opinion, and past data analysis. Combining these approaches is the most efficient way to determine the rule base (An et al., 2008; Ma et al., 2007). A fuzzy rule was developed in terms of linguistic variables of input risk parameters: P, E, C, and the output RL. A person uses a fuzzy linguistic scale as a procedure for measuring real-life situations. The set of scale values of some fuzzy linguistic scale is a collection of fuzzy sets defined on the same universe (Ryjov, 2003). The linguistic variables are represented by fuzzy sets that are developed from collected previous accident data, and the fuzzy sets are portrayed by MFs. A typical example of a fuzzy rule in underground mine risk assessment appears as below:

If P is 'Almost certain' and E is 'Frequent' and C is 'Minor', Then RL is 'Medium'.

The next step in the design stage is to seek experts' opinion on values of the risk parameters for each hazard identified at the event level and relative importance/weights of the risk parameters. In the absence of precise data, the experts' opinion on risk parameters was collected using linguistic variables and accordingly they are modelled using fuzzy set theory. The experts' opinion on weights of the risk parameters was collected using the AHP technique. Practically, it is impossible for a single manager or engineer to consider all relevant aspects of an underground mine. Therefore, risk assessment in underground mines includes experts with different backgrounds and experience. Each expert may have a different impact on the final judgement.

Let us consider the number of experts be 'N,' a number of hazards (E) identified be 'm', and the number of hazard factors be 'n'. Let e_{ij} be the judgement of *i* hazard for *j* criteria. Then we get N matrices of type E = $[e_{ij}]_{m*n}$. Then all experts' opinions on risk parameters of each particular event are aggregated to get an overall quantified value (Mandal et al., 2015). The arithmetic mean aggregation (Fasanghari & Roudsari, 2008; Pandey et al., 2012) operator defined on triangular fuzzy numbers (a_1, b_1, c_1), (a_2, b_2, c_2) … (a_n, b_n, c_n) delivers the result as (x, y, z)

Where, $x = 1/n \sum_{k=0}^{n} a_k,\ y = 1/n \sum_{k=0}^{n} b_k,\ z = 1/n \sum_{k=0}^{n} c_k$ (3.2)

After aggregating the experts' opinion, defuzzification of risk parameters should be done. For defuzzification of triangular fuzzy risk parameters, centroid defuzzification (Narayanamoorthy & Maheswari, 2012; Wang, 2009) method was used. If the aggregated fuzzified output A = (x, y, z), then the formula for the centroid method is as follows:

$$Centroid\ (A) = \frac{x+y+z}{3} \quad (3.3)$$

The crisp values obtained after the defuzzification method are used as inputs in the fuzzy logic risk estimation stage to calculate the RLs of the hazards and in VIKOR risk prioritization stage to rank the hazards at the event level.

3.4.3. Fuzzy logic - Risk estimation stage

In the fuzzy logic-risk estimation stage, the RL of each hazard at the hazardous event level is calculated by assessing the risk based on the P, E, and C values. Fuzzy logic allows imprecision or approximate information in the risk analysis process (Ghasemi & Ataei, 2013; Ma et al., 2007). In this methodology, Mamdani fuzzy inference system (Lee, 2006) was used as it is intuitive and well suited for human input. As the in-depth analysis of general fuzzy logic can be found in many works of literature (Ross, 2010; Zadeh, 1965), this section only provides a brief explanation of Mamdani fuzzy logic system. The main phases of the Mamdani fuzzy inference system to calculate RLs at hazardous event level are fuzzification, rule evaluation, defuzzification.

3.4.3.1. Fuzzification

The data collected from the preliminary stage is usually used as input, but if the collected data are uncertain or does not exist, then the experts' opinion gathered from the design stage is used as input data in the fuzzification phase. In many situations, in the mining industry, the data may not exist, so the experts' opinion collected was considered in this thesis. The input values of hazardous events collected from experts are crisp values. The steps in fuzzification are, the crisp input values are translated into fuzzy sets containing linguistic concepts, and the MFs are applied to the measurements, and a membership value is determined (Ross, 2010). Triangular fuzzy numbers are most generic class fuzzy numbers with linear MFs. For that reason, triangular MFs finds broad application in modelling linear uncertainty problems rather than trapezoidal fuzzy numbers. Also due to simplicity in the mathematical demonstration and easy to computation, Triangular MFs were used in this thesis to represent the input and output parameters graphically. A triangular MF converts the linguistic scales in the range of 0-1 using the equations 3.4 and 3.5.

$$\mu(x; a, b, c) = \begin{cases} 0, \ x < a \\ (x-a)/(b-a), \ a \leq x \leq b \\ (c-x)/(c-b), \ b \leq x \leq c \\ 0, \ c < x \end{cases} \tag{3.4}$$

$$\mu(x; a, b, c) = \left(max \left(min \left(\frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right) \right) \tag{3.5}$$

Where a, b, c are the parameters of the linguistic scale and x is the range of the input parameters.

3.4.3.2. Rule evaluation

In the rule evaluation process, the fuzzy inference system maps inputs and rules to calculate the fuzzy output, i.e. RL, using fuzzy set theory. Fuzzy inference mechanism is based on the compositional rule of inference proposed by Zadeh (1965). In this methodology, the 'MIN' operator was used for combination and implication operations. An implication method states how a fuzzy logic controller scales the MFs of an output linguistic variable based on the rule weight of the corresponding rule. The fuzzy outputs were aggregated by using the 'MAX' operator. Aggregation process is where the outputs of each rule are combined into a single fuzzy set (MathWorks, 2015).

3.4.3.3. Defuzzification

The output generated by the fuzzy inference system will always be fuzzy in nature. Therefore, to convert the fuzzy output to crisp output, defuzzification is needed. Centroid defuzzification method was used to get a crisp value from the aggregated fuzzy set. Centroid of area defuzzification method for establishing the output is expressed in equation 3.6.

Centroid of area, $z^* = \int \mu A(z).zdz \Big/ \int \mu A(z)dz$ (3.6)

Where, z* is the crisp value for the z output, and μA(z) is the aggregated output membership function.

After defuzzification, the fuzzy inference system gives a crisp output value. The crisp values obtained are used to express the RLs of all the identified hazards at the event level. The risk level (RL_{HG}) of a hazard group is determined by the summation of all the RLs (RL_{Ei}) of hazard events of that particular hazard group.

$RL_{HG} = \sum_{i=1}^{n} RL_{Ei}$, i = 1, 2,….n (3.7)

Where, RL_E is the risk level at hazardous event level. In the fuzzy reasoning approach, the weight contribution of risk parameters was considered as equal, which is not true in practice. The RL of some hazard events may have same RL as other hazards events, making it hard the prioritize the hazard events. Therefore, to overcome these limitations, the VIKOR method was applied to prioritize all the hazards events.

3.4.4. VIKOR - Risk prioritization stage

The crisp values of experts' opinion and weights obtained in the design phase were used as inputs in the VIKOR risk prioritization stage. The main aim of this stage is to develop a compromise ranking mechanism so that remedial actions can be ordered accordingly. Assuming that each alternative is evaluated according to each criterion function, the compromise ranking could be performed by comparing the measure of closeness to the ideal alternative. The multi-criteria measure for compromise ranking of hazards is developed from L_p matrix. If E_1, E_2… E_m are the various hazards, f_{ij} denotes the rating of *i*th aspect of hazard E_m. E_i for *j* criteria, if we have *n* criteria then, L_p matrix can be defined as follows (Zeleny, 1982):

$$L_{p,i} = \left(\sum_{j=1}^{n} \left[\frac{w_j(f_j^* - f_{ij})}{f_j^* - f_{ij}} \right]^p \right)^{1/p} \quad (3.8)$$

$1 \leq p \leq \infty$, i = 1, 2, … m.

Within the VIKOR method $L_{1,i}$ (as S_i in equation 3.9) and $L_{\infty,i}$ (as R_i in equation 3.10) are used to formulate ranking measure. The solution obtained by $\min_i (S_i)$ is with a maximum group utility, and the solution obtained by $\min_i (R_i)$ is with a minimum individual regret of the opponent. The compromise ranking algorithm VIKOR has the following steps (Opricovic & Tzeng, 2004):

The first step is to find the best (f_i^*) and worst (f_i^-) criteria solution for all risk parameters. *j =1, 2, 3,..,n.*

$f_j^* = \max_i e_{ij}$, $f_j^- = \min_i e_{ij}$, if the jth function represents a benefit,

$f_j^* = \min_i e_{ij}$, $f_j^- = \max_i e_{ij}$, if the jth function represents a cost.

In this thesis probability, exposure and consequence were cost criteria. The next step is to calculate the values S_i and R_i using equation 3.8.

$$S_i = \sum_{j=1}^{n} w_j \frac{(f_j^* - e_{ij})}{(f_j^* - f_j^-)} \tag{3.9}$$

$$R_i = \max_i w_j \frac{(f_j^* - e_{ij})}{(f_j^* - f_j^-)} \tag{3.10}$$

Where, w_j represents the weight of the risk parameters of the *j*th criteria. The next step is to compute the index values of Q_i using equation 3.8.

$$Q_i = v \left(\frac{S_i - S^*}{S^- - S^*}\right) + (1 - v)\left(\frac{R_i - R^*}{R^- - R^*}\right) \tag{3.11}$$

Where,

$$S^* = \min_i (S_i) \tag{3.12}$$

$$S^- = \max_i (S_i) \tag{3.13}$$

$$R^* = \min_i (R_i) \tag{3.14}$$

$$R^- = \max_i (R_i) \tag{3.15}$$

v is the weight factor for the maximum group utility, usually v = 0.5 is choosen.

Then rank the hazards by arranging the group utility (S), individual regret of the opponent (R), and ideal solution index (Q) values in descending order, which will produce three ranking lists. The final step in this stage is to propose a compromise solution. The hazard E_1 is the best ranked by the measure Q (minimum) if the following two conditions are satisfied:

Condition 1: Acceptable advantage: Q (E_2) - Q (E_1) $\geq$ DQ, where E_2 is the hazard (alternative) having the second position in the ranking list by Q; and DQ = $\frac{1}{(m-1)}$

Condition 2: Acceptable stability in decision making: The hazard E_1 must also be the best ranked by S or/and R. This compromise solution is stable within a decision-making process, which could be ‘‘voting by majority rule’’ (when $v > 0.5$ is needed), or ‘‘by consensus’s’’ ($v = 0.5$), or ‘‘with veto’’ ($v < 0.5$).

If one of the above conditions is not satisfied, then a set of compromise solutions is proposed as follows:

- E_1 and E_2 if only the condition ‘2’ is not satisfied or
- E_1, E_2, . . E_m if the condition ‘1’ is not satisfied; E_m is determined by the relation Q (E_m) – Q (E_1) < DQ for maximum ‘m’ (the positions of these hazards are ‘in closeness’).

The minimum value of Q is considered as the hazard with low risk associated with it. The compromise ranking thus developed will have maximum overall group utility and least individual regret. The compromise solution could be the base for negotiations, involving the decision makers’ preference by risk parameter’s weights.

3.4.5. AHP - Risk estimation stage

After evaluating the RL of all the identified hazards in the hazardous event level and prioritizing them, the proposed risk assessment methodology moves to estimate risk at the hazardous group level. In this stage, AHP was employed to determine the relative importance of each hazard factor, so that the risk assessment can be advanced from hazardous event level to hazardous group level and finally to mine level. AHP calculates weights by carrying out a pairwise comparison of the hazard factors. In general, AHP consists of a questionnaire for comparison of each hazard factor. In pairwise comparison, all the hazard factors are compared with each other to find out which hazard factor is riskier than the other is and how much risk it is in comparison with the other. Pairwise comparisons of the hazard factors at the group level are prepared by using Saaty (1990) ratio scale as shown in Table 3.6.

Table 3.6 Saaty's AHP scale

Intensity of importance in sub-criteria	Explanation	Scale
Equal Importance	Two hazard factors contribute equally	1
Between equal importance and weak importance	When compromise is needed	2
Weak importance	Experience and judgment slightly favour one hazard factor over another	3
Between weak and strong importance	When compromise is needed	4
Strong importance	Experience and judgment strongly favour one hazard factor over another	5
Between strong and very strong importance	When compromise is needed	6
Very strong importance	A hazard factor is favoured very strongly over another	7
Between very strong and absolute importance	When compromise is needed	8
Absolute importance	One hazard factor over another is of the highest possible affirmation	9

Let G_1, G_2, ..., G_n, as shown in Figure 3.7, are the hazard factors at the group level, e_{ij} represents the judgement on the hazard factors G_i, G_j., then the pairwise matrix e_{ij} yields as follows:

$$e_{ij} = \begin{bmatrix} 1 & G_{12} \cdots & G_{1n} \\ \vdots & \ddots & \vdots \\ \frac{1}{G_{1n}} & \frac{1}{G_{2n}} \cdots & 1 \end{bmatrix}$$

This requires $n(n-1)/2$ comparisons, where n is the number of hazard factors with the consideration that diagonal hazard factors are 1 and other hazard factors will be the reciprocals of the earlier comparisons. The next step after having a comparison matrix is to calculate the normalized Eigenvector of the matrix, which gives the relative importance (Weight, W) of the various hazard factors being compared. The normalized Eigenvector of the matrix is calculated by dividing each element of the matrix with the sum of its column and averaging across the rows. The C.I and random index (R.I) are utilized to verify the consistency of the comparison matrix (Consistency Ratio, (C.R)). Saaty (1990) has defined C.R as follows:

$$C.R = \frac{C.I}{R.I} \tag{3.16}$$

Where,

$$C.I = \frac{\lambda_{max} - n}{n-1} \tag{3.17}$$

λ_{max} is the Principal Eigenvalue. Principal Eigenvalue is the summation of products between each hazard factor of Eigenvector and the sum of columns of the reciprocal matrix. R.I is the average consistency index, which is given by Saaty and Vargas (1991), as presented in Table 3.7. If C.R < 0.1, then the experts' judgement is accepted; otherwise, judgement should be changed until C.R < 0.1.

Table 3.7 R.I values

n	**2**	**3**	**4**	**5**	**6**	**7**	**8**
R.I	0	0.52	0.90	1.12	1.24	1.32	1.41

On obtaining the Ws of hazard factors, the RL_G at the group level are reformed by combining the W_{Gi} and RL_{HG} as shown in equation 3.18.

$$RL_G = \sum_{i=1}^{n} RL_{HGi} W_{Gi},\ \text{i} = 1, 2, \ldots \text{n} \qquad (3.18)$$

Where, W_G is the weight of the hazard factors at group level. The overall RL of the mine level can be calculated by summation of all RL_G obtained from the group level.

$$RL_{MINE} = \sum_{i=1}^{n} RL_{Gi} \qquad (3.19)$$

3.5. Study Area

For the present study, six underground coal mines were chosen from the states of Odisha and Madhya Pradesh. Figure 3.8 represents the geological map of Indian with location points of six mines. Mine-1, mine-2 are located in Orient area, mine-3 is located in Talcher area of Mahanadi Coalfields Limited and mine-4, mine-5, mine-6 are located in Johilla area of South Eastern Coalfields Limited. Both the companies are the subsidiary mines of CIL. In this study, mine-1, mine-2, mine-3 were selected based on the dangerous occurrence and geological disturbances present in the mines. Mine-4, mine-5, mine-6 were selected as they were termed as accident prone mines by SECL. The salient geological and mining-related information of all the study areas are shown in Table 3.8.

Bord and pillar method is the most commonly employed technique for coal production in Indian underground coal mines. Bord and pillar mining method comprises two stages i.e., "Development" and "Depillaring". Sometimes both these stages proceed concurrently. In development, pillars are formed by driving a network of galleries, of which one set is generally parallel to the dip and the other set is parallel to the strike cutting the former at right angles. In depillaring, the coal pillars formed are extracted after the development of the mine. Generally, the bord and pillar mining method is carried in one of three ways (Hustrulid & Bullock, 2001), i.e.,

- Develop the entire area into pillars and then extract the pillars starting from the boundary.
- Develop the area into panels and extract pillars subsequently panel-wise. This is called as panel system of mining.
- "Whole" followed by "Broken" working in which the mines is opened out by a few heading only and there after development and depillaring go on simultaneously starting from the boundary.

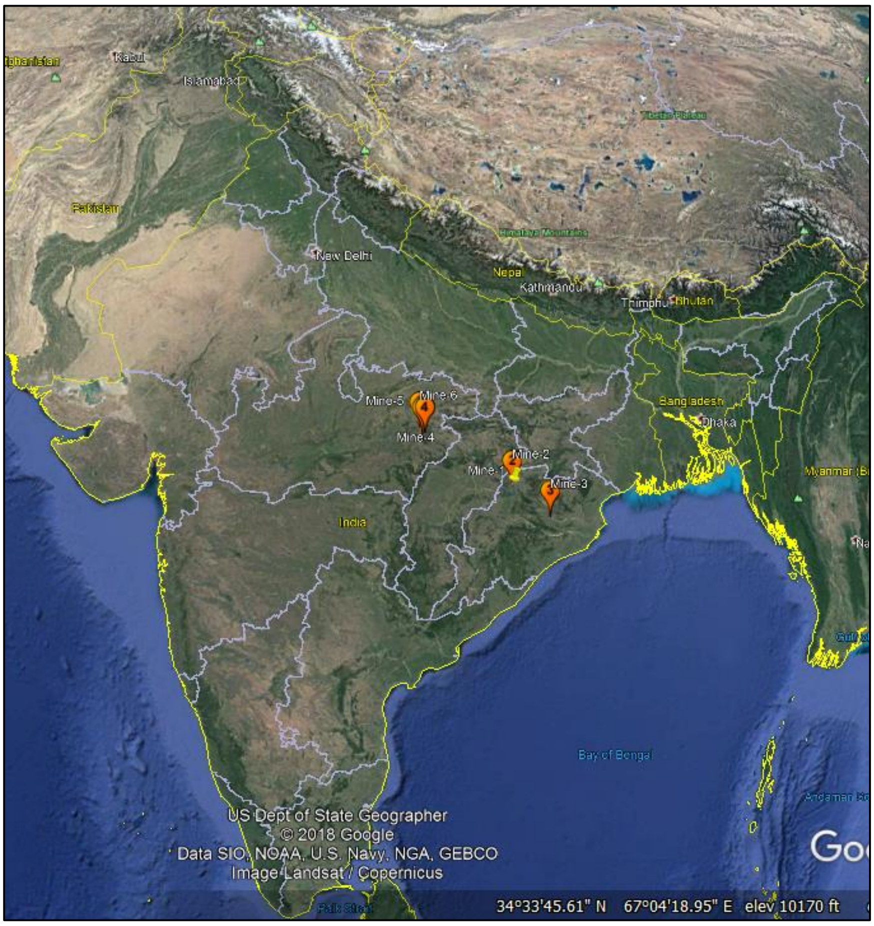


Figure 3.8 Location of study areas

Most of the Indian underground coal mines are either mechanised or semi-mechanised. The types of machinery commonly used in underground coal mines are load-haul-dumpers, side-discharge-loaders, universal drill machines, handheld drill machines, rope haulage, conveyors, ventilation fans, dewatering pumps, shuttle cars and locomotives (DGMS, 2015).

Table 3.8 Geological and mining-related information of the study areas

	Mine 1	**Mine 2**	**Mine 3**	**Mine 4**	**Mine 5**	**Mine 6**
Year of opening	1968	1955	1928	1983	1944	1884 (1973 came under CIL)
Number of seams worked	4	4	2	2	3	3
Depth of seam (range in meters)	18-282	25-220	94-158	18-150	15-135	15-140
Thickness of seam (range in meters)	18-22	25-30	5-9	2.5-4	8-10.1	3-3.6
Mining method	Bord and pillar	Bord and pillar	Bord and pillar, Depillaring with sand stowing	Depillaring with caving method	Bord and pillar	Bord and pillar
Face mechanization	Semi-mechanized	Semi-mechanized	Semi-mechanized	Semi-mechanized	Semi-mechanized	Semi-mechanized
Out-by coal transportation	Belt conveyor, LHD	Belt conveyor, LHD	Belt conveyor, SDL, haulage	Belt conveyor, SDL	Belt conveyor, SDL, haulage	Belt conveyor, SDL
Roof support	Full column cement grouted bolts	Full column cement grouted bolts	Girders, Roof bolts	Roof bolting	Full grouted roof bolts	Roof bolting
Degree of gassiness	Degree-II	Degree-II	Degree-I	Degree-I	Degree-I	Degree-I
Fire history	Yes	Yes	No	Yes	Yes	No

3.5.1. Description of Mine-1

The mine-1 is located west of Ib river and is about 2.5 km due north of Brajrajnagar railway station. The leasehold area of the mine is 11.16 sq.km. The physical map of the mine-1 is shown in Figure 3.9. The thickness of the seam is 18–22m and its gradient is 1 in 10.5. The seam is divided into sections 1, 2, 3 and 4. The thickness of the sections is 2.44m, 1.61m, 2.13m, and 2.20m respectively. The depth of the working varies from 18m to 282m.

Method of working is by the bord-and-pillar method using solid blasting technique with wedge cut pattern. P-5 type permitted explosives and delay detonators are used for blasting. LHD machines onto pony/gate belts in the working districts load blasted coal, which in turn discharges coal in the bunkers. After that, this coal is transported to surface bunker through a series of trunk conveyor belts. Materials and equipment that are required for normal functioning of the mine are transported to the underground through a series of haulages, namely direct haulage, tugger haulage and endless haulages. One exhaust type mechanical ventilator is installed on the surface of the mine, and there are four intake airways. The accident statistics of the mine are presented in Table 3.9. The history of dangerous occurrences in the mine are as follows:

Figure 3.9 Mine-1, Orient area, MCL

- There was a history of fire occurrence in the mine due to spontaneous heating in the years 1996, 2005, 2015. In the years, 2005 and 2015, the mine was sealed from the surface and was successfully reopened for production in the later years.
- There is an aquifer strata present at 30m above the seam 1, which if penetrated accidentally/incidentally may lead to a sudden inrush of water.
- A small roof fall at 78L/4th main dip is giving away 400-500 gallons per minute of water throughout the year.

Table 3.9 Accident statistics of mine-1

Year	Number of accident		
	Fatal	Serious	Reportable
2001	0	1	13
2002	0	0	9
2003	0	1	7
2004	0	2	1
2005	0	2	2
2006	1	0	2
2007	0	0	0
2008	0	0	3
2009	0	0	3
2010	0	0	2
2011	1	1	2
2012	0	0	0
2013	0	1	1
2014	0	1	0

2015	0	0	0
2016	0	0	0

3.5.2. Description of Mine-2

The mine is located about 3.5km on the south of Jharsuguda-Raipur road and about 2km north of Brajrajnagar railway station. The leasehold area of the mine is 18.57 sq. km. The physical map of the mine-2 is shown in Figure 3.10. The average thickness of the seam varies from 25m to 30m including bands. The seam is divided into four sub-seams 1, 2, 3, and 4. The thickness of the sub-seams is 2.59m, 2.22m, 2.69m, and 3m respectively. Mining activities are limited to sub-seam 4 only. The thickness of sub-seam 4 is 3.05m, depth is 160m, and its gradient is 1 in 30.

Figure 3.10 Mine-2, Orient area, MCL

Coal is excavated by the bord-and-pillar method using solid blasting technique with wedge cut pattern. P-5 type permitted explosives and delay detonators are used for blasting. Blasted coal is loaded by LHD machine onto pony/gate belts in the working districts, which in turn discharges coal in the bunkers. After that this coal is transported to surface bunker through a serious of trunk conveyor belts. Materials and equipment that are required for normal functioning of the mine are transported to the underground through a series of haulages, namely direct haulage, tugger haulage and endless haulages. Two exhaust type mechanical ventilators are installed on the surface of the mine. While one main mechanical ventilator provides the adequate ventilation to the workings of the mines, another one is provided as standby. Two auxiliary fans were also installed to provide adequate ventilation at the working face. The following are the two incidents of fire occurrences in the mine:

- In 1980, fire/heating was detected in old sealed off area at 48SL of 7th incline and the area was sealed successfully.
- In 1981, fire/heating was detected at 46 NL of 6th incline and the area was sealed successfully.

3.5.3. Description of Mine-3

The mine is located in Talcher town. The leasehold area of the mine is 11.46 sq. km. The physical map of the mine-3 is shown in Figure 3.11. There are two seams in the mine, i.e. seam-I, seam-II. In seam-I, there are two working sections: bottom section and top section. The thickness of the bottom and top section varies from 5m to 9m and 1.2m to 3.2m respectively. The Rock Mass Rating (RMR) value of the bottom section is 42, and the top section is 51.6. Seam-II is overlying over seam-I, which occurs in two small patches at quarriable depth in the western portion of the mine.

Figure 3.11 Mine-3, Talcher area, MCL

Presently, depillaring with stowing is being carried out at the bottom section, and development work is going on in the top section of the seam-I by SDLs. There are two shafts present in the mine. Shaft-I is electrically operated and is used for coal transportation by skip hoisting. Shaft-II is steam operated and is used for men and material transportation. Blasted coal is loaded by SDL on to belt conveyor, and the belt conveyor loads the coal in mine cars. The mine cars dump the coal on to skip with the help of tub tippler. Finally, skip dumps the coal in Coal Handling Plant (CHP) from where coal will be dispatched through trucks. Some geological features of the mine are given below:

- A major fault of 150m of down throw towards north has passed along the northern side near the mine boundary.
- A fault of 85m of down throw towards south has passed south side of the mine property.
- A fault of 20m down throw towards north has passed over bottom section panels.
- A fault of about 9m down throw towards north has passed near pit bottom.

3.5.4. Description of Mine-4

The mine is situated 2km due south of Birsinghpur railway station. The leasehold area of the mine is 11.58 sq. km. The physical map of the mine-4 is shown in Figure 3.12. The thickness of the seam is 2.5m to 4m. The seam is divided into two sub-seams, i.e. top and bottom. RMR of top and bottom sub-seam is 42 and 48 respectively. The depth of the working varies from 18m to 150m.

Figure 3.12 Mine-4, Johilla area, SECL

Both the sub-seams are completely developed, and depillaring with caving method is adopted for coal excavation. The coal is loaded by SDL machine onto conveyor belts in the working districts, which in turn discharges coal to the surface bunker, from where coal will be dispatched through trucks. Materials and equipment that are required for normal functioning of the mine are transported to the underground through direct haulage. One axial flow type mechanical ventilator is installed on the surface of the mine. Seven faults have been found in the mine having a throw of 5m to 50m that affected both the top and bottom sub-seams. There is one incident of spontaneous heating in 2005; the incident was contained successfully by sealing the panel.

3.5.5. Description of Mine-5

The mine is located in the western side of Johilla river and is about 5km away from Nowrozobad railway station on Katni-Bilaspur main line of South Eastern Central Railway. The leasehold area of the mine is 17.69 sq. km. The physical map of the mine-5 is shown in Figure 3.13. The thickness of the seam is 8-10.1m, and its gradient is 1 in 5. The depth of the working varies from 15m to 135m. The seam is divided into three sub-seams, i.e. 1, 2, and 3. Development work is going on in sub-seam 3 only. The average thickness of sub-seam 3 is 1.5m.

Figure 3.13 Mine-5, Johilla area, SECL

Coal is excavated using the bord-and-pillar method. Blasted coal is loaded by SDL machine onto pony belts in the working districts, which in turn discharges coal in the bunkers. After that this coal is transported to underground bunker through a serious of trunk conveyor belts. From the underground bunker, coal is loaded into tubs and brought to the surface by a series of haulages. From surface, coal is transported to railway siding by tippers. Dispatch to the linked consumers is being carried out through railways.

Water accumulated in the goaved out areas of 3rd sub-seam and old workings of 1 and 2 sub-seams are dewatered regularly by using two 1000 gallons per minute submersible pumps. A fault of about 7m down throw towards east has passed over 2nd sub-seam panels.

In this mines, spontaneous heating occurrences were detected in the year 1962, 1964, 1969, 1970, 1971, 1972, 1979, which were successfully contained by sealing off the panels.

3.5.6. Description of Mine-6

The mine is situated near Umaria. Its latitude is N 33^0 30' to N 33^0 33', and its longitude is E 80^0 47' to E 80^0 53'. The physical map of the mine-6 is shown in Figure 3.14.

Figure 3.14 Mine-6, Johilla area, SECL

The seam is divided into three sections 1, 2, and 3. DGMS prohibited the working in section-1 due to heavy seepage of water. The section-2 was developed and depillared by wide and stall method. Development working is going on in section-3 only. Method of working is done by the bord-and-pillar method. Blasted coal is transported with SDL machine and belt conveyors in series. There is no record of the history of dangers occurrences due to inundation, or fire.

3.6. Application of the Developed Methodology

The qualitative and quantitative risk assessment methods presented in this chapter are used for evaluating safety risks in mine-1. In the mine-1, FMEA was used to evaluate hazards related to belt conveyor system, rope haulage system and LHD, and WRAC was used to assess safety hazards related to ground movement, belt conveyor system, rope haulage system, LHD, blasting, electricity, inundation, and dust, gas and other combustible materials. FTA was applied to evaluate the root causes of the accidents occurred in mine-1 and ETA was applied to determine the consequential events of various mining situations.

The details of the application of qualitative and quantitative techniques in mine-1 and their results are discussed in Chapter 4.

The proposed methodology presented in this chapter was used to evaluate safety risks in underground coal mines. The development of the preliminary and design stages of the proposed methodology was performed in mine-1. A GUI was developed based on the Mamdani fuzzy logic, VIKOR, and AHP techniques for risk evaluation and prioritization at the hazardous events level, and risk evaluation at the hazardous group level and overall mine level. The GUI was used for evaluating safety risks in mine-1. To further validate the applicability of the proposed methodology to other mines, it was applied to five more mines, i.e. mine-2, mine-3, mine-4, mine-5, and mine-6. The details of the application of the proposed methodology to six underground coal mines and their results are discussed in Chapter 5.

3.7. Chapter Summary

In this chapter, a comprehensive methodology was developed in the form of different sections for evaluating risk in mines. The methodology is divided into two sections: existing risk assessment techniques, i.e. qualitative and quantitative approaches, and the proposed risk assessment method. The procedural steps of both risk assessment techniques and the proposed methodology were presented in this chapter. The information of the studied mines where the developed methodology was applied was also presented in this chapter.

CHAPTER 4

QUALITATIVE AND QUANTITATIVE APPROACHES FOR SAFETY RISK ASSESSMENT IN UNDERGROUND COAL MINES

4.1. Introduction

Risk assessment of a task can be performed using either qualitative, quantitative or both approaches. Due to the lack of extensive application of risk assessment techniques to various mining operations, the type of approaches that were appropriate for risk assessment in the mining industry is not clear. In the previous chapter, the qualitative and quantitative approaches were discussed. In this chapter, the qualitative and quantitative approaches were applied to an underground coal mine and the results obtained were presented.

4.2. Data Collection

As part of data collection, the headquarters of CIL, its subsidiary companies, i.e. MCL, SECL, BCCL headquarters, and DGMS, Dhanbad were visited many times. The DGMS is a governing agency under the Ministry of Labour and Employment in India that deals with matters relating to occupational safety, health and the welfare of persons employed in mines. The purpose of these visits is: (i) to collect accidental data to perform statistical analysis (ii) to gain knowledge on the risk assessment methodologies that are being used in the Indian mines and (iii) to interact with the safety executives, who were trained on risk assessment through the Safety in Mines Testing and Research Station (SIMTARS), Australia.

The mine-1 was also visited a number of times. The purpose of these visits is: (i) to collect the detail accident statistics, incident reports and inspection reports from 2001 to 2016 (ii) to perform the FMEA and WRAC analysis (iii) to develop the rule base for fuzzy inference system and (iv) to conduct questionnaire survey.

4.3. Qualitative Approaches

4.3.1. Failure Mode and Effects Analysis

In this study, FMEA was used to evaluate hazards related to mining equipment and machinery. In mine-1, there were 9 belt conveyor systems, 5 LHDs, and 13 haulage systems installed for coal and material transportation.

In the mine-1, a team consisting of a research scholar, a deputy manager and an overman performed FMEA study. The team identified the belt conveyor system, direct and indirect rope haulage system, haulage engine room, and LHD that could be examined by the FMEA tool. The team focused on examining each physical component of all the mining equipment. For each physical component, the possible failure modes were listed, and their effects were identified. Then the team used the DGMS (2002) scales to calculate the risk level based on the probability, exposure and consequence of the identified failure modes. The type of keywords used to identify the failure modes were mechanical, hydraulic, electrical, thermal, and radiation failures. In this study, only the failure modes that cause injury to workers were considered. Other types of effects like increased cost of operation, damage to equipment, damage to the environment, loss of production, process interruption, and reduced quality of production were not considered. The FMEA of belt conveyor, rope haulage, haulage engine room and LHD is presented in Table 4.1. In FMEA, the existing control measures were reviewed, and additional control measures were also documented.

Table 4.1 FMEA of mining machinery in mine-1

Component	Failure Mode	Failure Effect	Consequence	Exposure	Probability	Risk Score C*E*P	Control measures
Belt conveyor							
Belt	Improper belt joining	Injury to the operator, e.g. friction burns, cuts, abrasion impact with the belt, and drawing-in	0.001	1.5	3	0.0045	• Proper belt joining shall be provided and it shall be inspected regularly • The operator should stand at a safe distance from the conveyor while it is in motion

	Deteriorated belt	Injury to the operator, e.g. friction burns, cuts, abrasion impact with the belt, and drawing-in	0.001	1.5	2	0.003	• Damaged belt shall be replaced immediately • The operator should stand at a safe distance from the conveyor while it is in motion
	Fumes from the fire on belt	Chance of suffocation (Asphyxiation)	0.3	0.5	1	0.15	• Firefighting equipment shall be provided • Fire detection alarm system shall be provided
	Loose belt	Slip occurs between the drive pulley and belt causing friction which may ignite coal spillage or belt	0.3	0.5	1	0.15	• Tighten the belt tension whenever required
Idlers	Unguarded idlers	Drawing-in, injury to the operator	1	3	10	30	• Guards shall be provided around all the moving machine parts to protect workers
	Deteriorated idlers	Generate frictional heat which may ignite coal spillage or belt, injury to the operator	0.001	0.5	3	0.0015	• Every idler shall be maintained in good working condition and shall be taken out of use at predetermined intervals according to the manufacturer's recommendations • Sufficient stock of spare idlers shall be kept at the mine to permit the periodical inspection and replacement • Firefighting equipment shall be provided
	Material build-up	Generate frictional heat which may ignite coal spillage or belt	0.01	2	10	0.2	• Material shall be removed whenever required • Firefighting equipment shall be provided
Tensioning arrangement	Unguarded tensioning arrangement	Drawing-in and crushing or injury to the operator while cleaning or maintaining or passing by	0.1	1.5	3	0.45	• The tensioning units shall be kept substantially fenced or guarded so that no person can get caught by the running belt or any moving part

Drive head which comprised the electric motor, coupling, gearing and snub pulleys	Unguarded drive head	Drawing-in and crushing or injury to the operator while cleaning or maintaining or passing by	0.3	1.5	1	0.45	• All the exposed rotating and forming parts of the drive head shall be kept substantially fenced or guarded so that no person can get caught by the running belt or any moving part
	Use of inflammable materials	Chance of fire	5	2.5	2	25	• Within 5m of the drive head, only non-inflammable or fire-resistant materials shall be used for support • Only fire-resistant hydraulic fluid coupling shall be used
	Arc fault on power cables	Chance of ignition of flammable material in the vicinity, the chance of fire	0.3	0.02	2	0.012	• All electrical parts of the conveyor shall be installed properly and maintained regularly
	Bearing failure	Leads to overheating which may ignite dust or spillage	0.0001	0.5	3	0.00015	• Coal spillage shall be cleaned regularly and whenever required • Drive head shall be inspected and maintained regularly
Tail end	Unguarded tail end	Drawing-in and crushing or injury to the operator while cleaning or maintaining or passing by	0.3	1.5	1	0.45	• The tail end shall be kept substantially fenced or guarded so that no person can get caught by the running belt or any moving part • The operator should not wear loose clothing
Chute	Jamming of chute due to improper screening	Chance of fire due to friction between the belt and coal	0.01	0.5	3	0.015	• Chute full detection/ shutdown system shall be provided • The proper screen shall be provided
Rope haulage							
Rope	Breakage of rope due to wear, rusting or improper splicing	Runaway of tubs, injury to workers	1	2.5	7	17.5	• Rope condition and joints shall be inspected and maintained properly • Improper or damaged ropes shall be replaced immediately • Overloading of tubs shall not be allowed
Clips or lashing chain	Improper or defective clips or lashing chain	Detachment of tub from the rope, runaway of tubs, injury to workers	1	1.5	3	4.5	• Only approved clips or lashing chain shall be used to attach tubs and rope • Clips and lashing chain shall be inspected and maintained regularly

Drawbar	Failure of drawbar	Runaway of tubs, injury to workers	1	2	3	6	• Only approved drawbars shall be used • Periodical inspection and maintenance shall be performed • Worn out and defective drawbar shall be replaced immediately
Capel or shackles	Defective capel or shackles	Runaway of tubs, injury to workers	0.1	1.5	1	0.15	• Only approved capel shall be used • Periodical inspection and maintenance shall be performed • Worn out and defective capel or shackles shall be replaced immediately
Track	Defective laying of track line	Derailment of tubs, injury to workers	0.3	2	10	6	• Proper maintenance of haulage track shall be performed
Tubs	Improper condition of tubs	Derailment of tubs, injury to workers	0.01	2	7	0.14	• Proper maintenance of tubs shall be performed
Tub buffers	Non-provision or non-functioning	Getting caught between tubs while coupling & uncoupling	1	0.5	3	1.5	• Tub buffers shall be provided and maintained properly
Sprags	Failure of sprags	Sudden movement of tubs, injury to workers	1	1.5	3	4.5	• Only good condition sprags shall be used • A regular inspection shall be performed
Haulage engine							
Drum, Surge wheel, Clutch and gears	Improper condition of the drum or surge wheel or clutch or gears	Hard to control haulage, injury to workers	0.3	0.02	1	0.006	• Condition of the drum, surge wheel, clutch and gears shall be inspected and maintained regularly
Brake (brake wheel and liners)	Failure of brakes	Injury to workers	1	0.02	2	0.04	• Inspection and maintenance of brake liners, wheel, lever and linkages shall be performed regularly • Defective or improper liners shall be changed immediately

LHD							
Brakes	Parking brake failure	Machine movement causing injury to the operator and other workers, damage to machine	1	0.02	2	0.04	• Parking brakes shall be inspected before starting the operation • Preventive maintenance shall be performed periodically • When the LHD is parked, the bucket should be lowered to the ground
	Service brake failure	Injury to the operator and other workers	1	0.02	2	0.04	• Service brakes shall be inspected before starting the operation • Preventive maintenance shall be performed periodically
Bucket	Improper condition of the bucket	Slippage of bucket tip plate during operation, injury to workers	0.1	0.02	1	0.002	• Checking and maintenance of bucket shall be performed regularly
	Improper condition of lift or tilt cylinder	Injury to workers and operator himself	0.1	0.5	1	0.05	• Checking and maintenance of lift and tilt cylinders shall be performed regularly
Engine and hydraulic system	Pilot switch not in order	Electrocution, chance of fire, injury to the operator and other workers	0.3	1.5	2	0.9	• Pilot switch shall be provided and maintained regularly
	Pressure relief valve not in order	Bursting of oil the tank and hoses causing injury to the operator and other workers	0.3	1.5	1	0.45	• All the pressure valves shall be adequately maintained to ensure proper release of the pressure valve
	Temperature switch or cut-off valve not in order	Damage to the machine, injury to workers	0.3	1.5	2	0.9	• Temperature switch or cut-off valve shall be inspected and maintained regularly • Temperature switch settings shall be set as per original equipment manufacturer's recommendations
	Dump valve not in order	Operational problem and risk associated with uncontrolled movement of the machine	0.1	0.02	1	0.002	• Regular checking and maintenance of dump valve shall be performed
	Oil leakage	Fire, injury to the operator and other workers	0.3	2	3	1.8	• Always maintain oil tank in good condition

Safety features	Non-provision or improper canopy	Injury to the operator	0.1	1.5	7	1.05	• The operator shall not be allowed to operate the machine without canopy • Canopy shall be inspected for any physical damage and maintain accordingly
	Head or rear light not working	Injury to the operator and other workers, damage to machine	0.3	1.5	1	0.45	• Head and tail lights shall be checked before starting the operation • Head and tail lights shall be replaced whenever required
	Audio-visual alarm or horn not working	Injury to workers	0.3	1.5	1	0.45	• Audio-visual alarm shall be checked before starting the operation • Preventive maintenance shall be performed periodically
	Footswitch or dead-man switch not working	Injury to the operator and other workers, damage to machine	0.3	1.5	1	0.45	• Regular checking and maintenance of dead man switch shall be performed
Tires	Bursting of tyre	Accidental dislodging of the wheel, injury to the operator and other workers	0.1	0.5	3	0.15	• Tyre pressure, the physical condition of tyre and condition of nut bolts shall be checked and maintained regularly
Flexible trailing cable	Improper reeling or unreeling	Damage to cable, uncontrolled runaway of the machine causing injury to the operator and other workers	0.3	1.5	2	0.9	• Preventive measures shall be taken to avoid improper reeling and unreeling • Cable shall be inspected and maintained regularly • Workers shall not be allowed to move along the plying path of the machine
	Poor or damaged flexible trailing cable	May lead to electrocution	0.3	2	3	1.8	• Flexible trailing cable shall be jointed and maintained properly • High strength cables shall be used
Gate-end box	Improper gate-end box earthing	Improper earthing cannot transmit a fault to the tripping mechanism of a switch may lead to electrocution	0.3	0.5	1	0.15	• Earthing shall be performed properly

4.3.3. Workplace Risk Assessment and Control

Unlike FMEA, WRAC tool is not limited to machine design changes. It can be applied to analyse a wide range of operations in mines. In the mine-1, a team consisting a research scholar, a deputy manager and an overman performed WRAC study. The objective of this study was set to identify the safety hazards of various mining situations. The team focused on general hazard identification and job/process mapping discussion aimed at introducing WRAC technique to the mining operations. The 5×5-risk matrix developed in CIL was used to assess the risk level of the identified hazards.

After the instructional aspects of the WRAC had been completed, the team identified critical safety operations that could be mapped and examined by the WRAC tool. The safety operations identified in mine-1 were related to ground movement, conveyor belt system, rope haulage system, LHD, blasting, electricity, inundation, and dust, gas and other combustible materials. The team then examined the activities associated with the safety operations. The safety hazards associated with workers' actions, machines/tools, work methods/ procedures and the overall work environment conditions in the underground coal mine were considered in this study. After examining the activities of the safety operation, the team then listed out the hazards related to all the identified safety operations, attempted to identify the associated risk for each hazard listed out and rank the associated risk. In this study, only the risks that cause injury to workers were considered. The likelihood and consequence were graded based on team personnel's experience. The risk assessment team then identified existing controls and new controls to manage the top associated risk. The WRAC analysis of ground movement, rope haulage system, conveyor belt system, LHD, electricity, blasting, inundation, and dust, gas and other combustible materials are presented in Tables 4.2–4.9 respectively.

Table 4.2 Risk ranking of hazards related to ground movement using WRAC tool

Hazards	Risks	Risk Ranking			Control measures
		Likelihood	Consequence	Score & Level	

Geologically disturbed areas or weak old supports	Roof and side may fall causing injuries to workers, chance of inundation	L1	C4	10 Medium	• Identify the geologically disturbed areas and mark them on the mine plan • Roof bolting with additional precautions shall be performed in geologically disturbed and weak old support areas
RMR not determined, and SSR not framed properly	Improper support may lead to the roof fall	L1	C4	10 Medium	• RMR shall be determined, on or before opening a new district • SSR shall be framed based on RMR
Poor knowledge of approved SSR	Under or over support, injury to workers	L2	C3	9 Medium	• Information shall be imparted by safety talks • Supports should be reviewed weekly
Weak roof or side conditions	Roof or side may fall causing injuries to workers	L3	C4	18 Medium	• If the roof or side conditions deteriorate, additional supporting shall be provided • Dressing of roof and sides shall be performed regularly
More height and width of galleries	Unbalanced stress on roof lead to the roof fall, gallery height of more than 3m may also lead to the side fall	L3	C3	13 Medium	• Height and Width are restricted as per DGMS permission • Accurate and precise surveying shall be performed • Additional supports shall be erected to strengthen the roof • Sides shall be supported with mesh and W-Straps
Poorly supported or unsupported roof	Chance of roof fall	L1	C4	10 Medium	• Roof shall be timely supported • Additional support shall be provided as and whenever required • Support gang shall advance in ascending order
Delay in support of freshly exposed roof	Endangering safety of face workers	L2	C3	9 Medium	• Temporary roof support shall be provided till the roof is supported with permanent supports • Proper follow up shall be performed in all three shifts
Poor quality of cement capsule and drill rods	Fake sense of roof support or deterioration of roof leads to roof fall	L4	C3	17 Medium	• Anchorage testing shall be performed regularly • Cement capsules and drill rods shall be visually tested • Strata monitoring cell shall be formed at unit level as well as sub-area level and area level

Less than adequate grout in the column	Fake sense of roof support or deterioration of roof leads to roof fall	L4	C3	17 Medium	• Anchorage testing shall be performed regularly • Roof bolting shall be performed under close supervision of District In-charge • Safety awareness among rock bolting support crew shall be developed
Unavailability of support material	Unsupported workings, chance of roof or side fall	L4	C3	17 Medium	• Blasting operation shall be halted until support work is completed • No work shall be performed without support • Buffer stock of at least one-day consumption shall be provided and maintained
Untrained or unskilled support crew	Poor workmanship, injury to support crew	L3	C3	13 Medium	• Proper training to support crew shall be provided • Untrained workers shall be deployed in direct supervision of trained workers
Poor supervision	Chance of roof or side fall, risk to the workers deployed under this individual	L4	C4	21 High	• Trained and experienced supervisors shall be deployed • No work shall be performed without supervisors • Regular training to supervisors and support personnel shall be provided
Improper testing and dressing	Weak layers may fall on working persons causing injuries	L4	C4	21 High	• All outbye galleries shall be tested and dressed weekly • Officers shall do random checks to verify and ensure the proper testing and dressing of roof and sides was performed regularly
Non-vertical alignment of galleries	Uneven distribution of stresses may lead to the roof or side fall, crushed floor and pillars	L3	C4	18 Medium	• Verticality of contiguous working shall be maintained by proper surveying • Timely extension of the centre line shall be performed
Lack of indicators in strata monitoring	No indication of strata deterioration, unexpected falls	L2	C3	9 Medium	• Load Shell, Tell-tale, spring type convergence recorder, sliding type convergence recorder, borehole extensometer shall be provided for strata monitoring
Water seepage	Roof and sides will become weak causing roof fall or side fall	L4	C2	12 Medium	• Weeping holes shall be made on the roof • Regular strata monitoring shall be performed

Presence of subsidence cracks and fissures on the surface above development panel	Chance of fire and explosion, chance of inundation, roof and side fall may occur, injury to workers, loss of property	L3	C4	18 Medium	• Subsidence area shall be monitored regularly • Subsidence cracks shall be filled by dozing or concreting if necessary

Table 4.3 Risk ranking of hazards related to rope haulage system using WRAC tool

Hazards	Risks	Risk Ranking			Control measures
		Likelihood	Consequence	Score & Level	
Deployment of an unauthorized or untrained trammer or clip-man	Injury to trammer or clip-man and other workers	L2	C2	5 Low	• Only authorized and trained trammers, and clip-man shall be deployed to work
Overloading of tubs	Breakage of rope, injury to workers	L2	C2	5 Low	• Trammers and supervisors shall be educated about the maximum number of tubs or maximum capacity of the material to be loaded
Defective rope or rope splicing	Breakage of rope, injury to workers	L2	C2	5 Low	• Proper care shall be taken in inspection, maintenance and replacement of defective rope and rope splicing
Defective or improper clips or lashing chain	Detachment of tub from the rope, injury to worker	L2	C2	5 Low	• Only approved clips or lashing chain shall be used to attach tubs and rope • Clips and lashing chain shall be inspected and maintained regularly
Unexpected movement of tubs	Workers get caught between tubs while coupling and uncoupling	L2	C2	5 Low	• Tub buffers shall be provided and maintained properly
Failure of drawbar	Runaway of tubs, injury to workers	L3	C3	13 Medium	• Drawbar shall be properly fixed with the chassis of the tub body • Good condition drawbars shall be used • Lock on drawbar shall be provided
Failure of sprags	Sudden movement of tubs, injury to workers	L2	C2	5 Low	• Only good condition sprags shall be used • Regular inspection shall be performed

Non-provision or improper maintenance of safety features like stop block, runaway switch, backstay, drag, catches, safety hooks, jazz rails, tub re-railers	Derailment of tubs, runaway of tubs, injury to workers	L2	C2	5 Low	• All the safety features shall be provided and maintained regularly
Improper laying and maintenance of track line	Derailment of tubs, injury to workers	L2	C2	5 Low	• Provision of proper maintenance of track line shall be properly laid and maintained regularly • Preventive maintenance of track line shall be performed
Improper maintenance of tubs and their fittings	Injury to workers, derailment of tubs	L2	C2	5 Low	• Tubs and their fittings shall be inspected and maintained regularly • Preventive maintenance shall be performed
Lack of precaution while haulage track line crosses travelling road	Injury to workers	L3	C2	8 Medium	• Zigzag fencing shall be provided, • Crossovers or under bridge shall be provided
Failure of signalling system	Injury to workers	L2	C2	5 Low	• Regular maintenance of signalling system shall be performed • Code of signalling shall be displayed at strategic places • Audio-visual alarm shall be provided
Haulage engine room					
Deployment of an unauthorized or untrained operator	Injury to workers	L2	C2	5 Low	• Only authorized and trained operator shall be deployed to work
Improper maintenance of engine room	Failure of haulage, injury to workers	L1	C2	3 Low	• Engine room shall be inspected and maintained regularly
Non-provision of guards	Injury to haulage operator and other workers	L3	C2	8 Medium	• Guards or fences shall be provided for rope, coupling and all moving parts
Improper maintenance of braking system	Failure of haulage brake, injury to workers	L1	C3	6 Low	• Inspection and maintenance of brake liners, lever and linkages shall be performed regularly

Table 4.4 Risk ranking of hazards related to belt conveyor system using WRAC tool

Hazards	Risks	Risk Ranking			Control measures
		Likelihood	**Consequence**	**Score & Level**	
Deployment of an unauthorized or untrained operator	Injury to the operator and other workers	L3	C4	18 Medium	• Only authorized and trained operator shall be deployed to work
Pre-start check not performed by operator	Injury to the operator and other workers, damage to machine	L3	C3	13 Medium	• Before starting the conveyor operation, the operator shall check all the safety devices, the gate-end box, belt joints, motor, coupling guard, and belt • The operator shall also communicate through telephone with chute operator
An operator wearing loose dress	Injury to the operator	L3	C3	13 Medium	• Operator shall not be allowed to work with loose clothing
Improper or inadequate cleaning of spillage coal in belt sides, drive heads and tail ends	Injury to the operator engaged for cleaning	L3	C3	13 Medium	• No person shall be allowed to clean belt while the belt is in motion • Longhand shovel with 'T' handle shall be provided • Fence or guards shall be provided around drive heads and tail ends
Inattentive chute opening	Injury to chute operator due to fall of lump while cleaning the chute	L3	C3	13 Medium	• Long crew-bar shall be provided • Proper screen shall be provided • Mechanical or hydraulic chute with lump breaker shall be provided
Breaking of coupling or bolts of coupling and non-provision of coupling guard	Injury to workers, damage to machinery	L3	C4	18 Medium	• Regular checking and tightening of bolts shall be performed • Coupling guard shall be provided
Inadvertent entry of a person in drive end or tail end or tension or discharge drum	Injury to person	L3	C4	18 Medium	• Guards shall be provided • Regular checking and maintenance shall be performed • Guards shall be interlocked with belt starter • Pre-start alarm shall be provided

Friction in the running belt due to spillage of coal and belt structure	Chance of fire	L3	C4	18 Medium	• Fire extinguishers shall be provided in operating condition at strategic places • Water spraying arrangement shall be provided • Fallen coal shall be cleaned regularly • Belt shall be regularly checked for proper alignment to prevent rubbing of the belt with the structure
Damaged idlers or rollers	Chance of fire	L3	C3	13 Medium	• Idlers and rollers shall be maintained regularly • Damaged idlers or rollers shall be changed regularly • Coal spillage shall be cleaned regularly
Worker crossing the belt to the other side or Inadvertent entry of a worker while the belt is moving	Injury to worker due to fall while crossing	L3	C3	13 Medium	• Crossover bridge shall be provided at every six pillar interval • Crossover bridge shall be used for crossing the belt
Failure of signalling system	Injury to workers	L3	C3	13 Medium	• Regular maintenance of signalling system shall be performed • Code of signalling shall be displayed at strategic places • Audio-visual alarm to be provided at every 200m length along the belt conveyor • Signalling system shall be interlocked with switch and starter • Two-way signalling system with audio-visual alarm shall be provided
Failure of pull cord and lockout switches	Injury to workers	L3	C3	13 Medium	• Pull cord switch shall be checked and maintained regularly • Lockout switches shall be used while repairing or maintaining conveyor belt

Table 4.5 Risk ranking of hazards related to LHD using WRAC tool

Hazards	Risks	Risk Ranking			Control measures
		Likelihood	**Consequence**	**Score & Level**	
Deployment of an unauthorized or untrained operator	Injury to the operator and other workers	L3	C3	13 Medium	• Only authorized and trained operator shall be deployed to work • Proper training shall be provided for the operator

Pre-start check not performed by operator	Injury to the operator and other workers	L3	C3	13 Medium	• Before starting the loading operation, the operator shall check all the safety devices, engine oil, transmission oil, hydraulic oil, electrical components, tyre, exhaust particulate filter • Checklists shall be provided to the operator
Improper condition of brakes	Injury to the operator and other workers	L3	C3	13 Medium	• Preventive maintenance of brakes shall be performed regularly • Secondary brakes, i.e. hand brakes shall be provided
Front or rear light not working	Injury to the operator and other workers	L3	C3	13 Medium	• Lights shall be checked and maintained regularly
Audio-visual alarm or Bell not working	Injury to workers	L3	C3	13 Mediu	• Audio-visual alarm or bell shall be checked and maintained regularly
Footswitch or dead-man switch not working	Injury to workers, damage to machine	L3	C3	13 Medium	• Footswitch or dead-man shall be checked and maintained regularly
Pilot switch not in order	Electrocution, chance of fire, injury to workers	L3	C3	13 Medium	• Pilot switch shall be checked and maintained regularly
Improper oil tank condition	Fire, injury to workers	L3	C3	13 Medium	• Oil tank shall be regularly inspected for any physical damages and repair shall be performed whenever required
Bad condition of tyre	Bursting of the tyre, accidental dislodging of the wheel, injury to the operator, damage to machine	L3	C3	13 Medium	• Tyre pressure, the physical condition of the tyre, and condition of nut bolts shall be checked and maintained regularly
Parking or standing of the machine at a gradient	Unexpected movement of the machine, injury to workers, damage to machine	L3	C3	13 Medium	• Strict instructions shall be passed not to park machine on gradient floor • Brakes shall be maintained regularly • The machine shall be parked properly at the parking place, and adequate height & width of the gallery shall be maintained

Plying of the machine in disturbed or unsafe areas	Flying of coal pieces due to the movement of the machine may cause injury to workers	L3	C4	18 Medium	• Fallen coal shall be cleared, and roadways shall be maintained properly • Workers shall not be allowed to move along the plying path of the machine • Caution board shall be displayed • Dressing of roof and sides shall be performed regularly
Improper condition of lift or tilt cylinders	Injury to workers and operator, chance of fire	L3	C3	13 Medium	• Preventive maintenance of lift and tilt cylinders shall be performed regularly • Pre-start check shall be performed
Improper canopy or canopy not provided	Injury to the operator	L3	C3	13 Medium	• Operator shall not be allowed to operate the machine without canopy • Canopy shall be inspected for any physical damage and maintain accordingly
Bypass dump valve or dump valve not in order	Operational problem and risks associated with the uncontrolled movement of the machine	L3	C3	13 Medium	• All the engine parts shall be inspected and maintained regularly
Unexpected movement of flexible tailing cable	Injury to workers	L4	C2	12 Medium	• Inadvertent entry of a LHD helper or other workers along the plying path of the machine shall be restricted

Table 4.6 Risk ranking of hazards related to electricity using WRAC tool

Hazards	Risks	Risk Ranking			Control measures
		Likelihood	**Consequence**	**Score & Level**	
Failure of protective devices	Chance of electric shock	L3	C3	13 Medium	• Damaged protective devices shall be repaired and replaced if necessary • Systems shall not be used without protective devices
Improper earthing	Chance of electric shock	L1	C4	10 Medium	• Earthing shall be performed properly • Proper earthing materials shall be provided
Defective earth pit and neutral pit	Chance of electric shock	L1	C4	10 Medium	• Earth, neutral pits and earth connections shall be inspected regularly and corrected if necessary

Improper maintenance of flameproof features	Chance of electric fire and explosion	L4	C4	21 High	• Flameproof features of all equipment shall be maintained regularly and properly • Leakages shall be rectified immediately • Adequate spare parts shall be provided for maintenance of flameproof features
Improper permanent cable joints (compounding)	Chance of fire, short circuit	L3	C3	13 Medium	• All the improper cable joints shall be identified and protected • Compounding of entry boxes and cable joints shall be performed properly
Poor insulations	Chance of fire, short circuit	L3	C3	13 Medium	• All the improper insulations shall be identified and rectified
Improper shutdown procedure	Chance of electrocution	L3	C4	18 Medium	• Awareness of proper shutdown procedure shall be improved • Proper shutdown procedure shall be followed
Improper fencing of installations	Chance of electrocution	L3	C3	13 Medium	• Temporary fencing arrangements shall be provided around all the installations
Faulty power cables	Chance of electrocution	L3	C3	13 Medium	• Faulty power cables shall be identified by regular inspection • Repair and replace faulty power cables as required
Housing of power cable along with signalling cable and lighting cable jointly	Chance of electrocution	L3	C3	13 Medium	• Proper isolation shall be provided between power cable, signalling cable and lighting cables
Improper maintenance of electric apparatus of equipment without proper precaution	Injury to electrician	L3	C3	13 Medium	• Proper maintenance of electric apparatus shall be performed regularly • Personal protective equipment shall be used • Proper tools in required quantity shall be provided
Unsatisfactory flexible trailing cable	Poor installation, a damaged cable may lead to electrocution	L3	C3	13 Medium	• High strength cable shall be used • Flexible trailing cable shall be properly joined and maintained regularly

Improper reeling or unreeling	Damage to cable, uncontrolled runaway of the machine causing injury to the operator and other workers, damage of the machine	L3	C3	13 Medium	• Preventive measures shall be taken to avoid improper reeling and unreeling • Cable shall be inspected and maintained regularly • Workers shall not be allowed to move along the plying path of the machine

Table 4.7 Risk ranking of hazards related to blasting operation using WRAC tool

Hazards	Risks	Risk Ranking			Control measures
		Likelihood	**Consequence**	**Score & Level**	
Deployment of an unauthorized or untrained blasting crew	Injury to workers entering the blasting zone, misfire	L3	C3	13 Medium	• Only authorized and trained blasting crew shall be deployed to work
Not following the blasting card system	Chance of workers entering the blasting zone	L2	C3	9 Medium	• Supervisor shall cross-check the blasting cards during underground visits • The supervisor shall also ensure that the blasting cards system is being followed
Drivage of joining gallery from both ends	Inadvertent entry of workers into the blasting area, blown out and blown through shots	L4	C3	17 Medium	• Blasting card system shall be strictly implemented • Parting register shall be maintained
Priming of explosives in unauthorized places	Accidental blasting	L3	C3	13 Medium	• Priming the explosives shall be performed only at face • Priming shall be performed under the supervision of Shift In-charge
Multiple operations at face while charging	Chance of injuries, accidental blasting	L3	C3	13 Medium	• Charging of explosives shall be performed only when drill machine is removed from the face
Improper or poorly maintained blasting tools	Accidental blasting	L2	C3	9 Medium	• Blasting tools shall be maintained regularly • Proper tools shall be made available in the district
Carrying of explosives and detonator together	Accidental blasting	L3	C3	13 Medium	• Proper containers with separate lock and key shall be provided for explosives and detonators

Shot firing from a source other than the exploder	Accidental blasting	L3	C4	18 Medium	• Only approved exploder shall be used for blasting
Shot firer engaged in other work	Lack of concentration , accidental blasting	L2	C2	5 Low	• Shot firer shall not be overloaded with other work
Improper dealing of misfire	Chance of fire, manual accident	L3	C3	13 Medium	• Misfire shall be dealt as per regulations and various guidelines given by DGMS
Blasting in a gassy seam	Chance of explosion	L3	C5	22 High	• Solid blasting shall be performed as per DGMS permission • Checking for the presence of inflammable gases shall be performed regularly • Water shall be sprayed before and after blasting

Table 4.8 Risk ranking of hazards related to inundation using WRAC tool

Hazards	Risks	Risk Ranking			Control measures
		Likelihood	**Consequence**	**Score & Level**	
Inaccurate drivage of face	Chance of inundation	L2	C2	5 Low	• Daily checking shall be performed with reference to survey • Rechecking shall be performed every week using survey instruments
Insufficient number of pumps or failure of pumps	Chance of inundation	L2	C2	5 Low	• Sufficient sump area shall be provided • Sufficient number of high head pumps and standby pumps shall be provided • Pumps shall be inspected and maintained regularly

Working near geological disturbances, i.e. faults, folds, slips	Chance of inundation	L2	C2	5 Low	• Geological disturbances shall be demarcated in different plans • 15m barrier shall be left against such disturbances • Sump area and pumping capacity shall be increased • More exploratory boreholes shall be drilled for determining exact geology of strata • A hydro-geological survey shall be carried out to find out the presence of the water body
Presence of surface cracks, fissures, subsidence	Chance of inundation	L3	C3	13 Medium	• Surface cracks, fissures, subsidence area shall be filled to avoid any inrush of water to underground
Old boreholes which are not sealed effectively	Chance of inundation	L2	C2	5 Low	• Boreholes shall be sealed, and the 3m barrier shall be maintained around the borehole • Boreholes shall be checked for every 3 months
Unexpected heavy rains and power failure	Chance of inundation	L2	C2	5 Low	• Stoppage of working in case of abnormal seepage of water • Workers shall be evacuated from underground

Table 4.9 Risk ranking of hazards related to dust, gas and other combustible materials using WRAC tool

Hazards	**Risks**	**Risk Ranking**			**Control measures**
		Likelihood	**Consequence**	**Score & Level**	
Explosion					
Improper sealing of extracted panels	Leakage of ventilation, chance of fire	L3	C4	18 Medium	• Sectionalisation stopping shall be erected. • All the sectionalisation stoppings shall be monitored regularly from the surface by using a Tele Monitoring System • Explosion proof stopping shall be provided if CH_4 exceeds more than 2%

Improper monitoring or inspection of gases in sealed off areas and old working areas which are not sealed off	Chance of explosion	L3	C4	18 Medium	• Sealed off areas and old workings shall be inspected once in 7 days by a competent person • Tele Monitoring System shall be used for monitoring underground operations
Huge coal dust deposition in the return airway	Chance of explosion	L1	C4	10 Medium	• Return airway shall be properly cleaned • Sprinkling of stone dust shall be performed to suppress coal dust
Leakage from sectionalisation stoppings	Chance of fire and explosion	L1	C4	10 Medium	• Regular monitoring and maintenance of sectionalisation stopping shall be performed • Stopping outbye of the previous stopping shall be erected, if required and balance pressure to avoid leakage of stoppings
Inadequate or non-functioning of gas detecting apparatus	Failure to detect gases during early stages may cause fire and explosion	L2	C4	14 Medium	• Sufficient number of gas detection, and monitoring instruments shall be provided • Calibration and maintenance of the instruments shall be performed regularly
Improper sampling of gases by supervisors	Incapability of monitoring the percentage of gases present, chance of fire and explosion	L2	C4	14 Medium	• Regular sampling shall be performed • Supervisors shall be properly trained • Retraining shall be provided to supervisors if required
Non-inter coupling of underground power with the main mechanical ventilator fan	Chance of spreading the accumulated igneous, noxious, toxic, inflammable gases to other areas	L1	C3	6 Low	• Main mechanical ventilator fan shall be inter-coupled with underground power
Gas cutting or welding work near a dusty area or any unauthorized area	Chance of fire and explosion, injury to workers	L2	C3	9 Medium	• Gas cutting or welding work shall only be allowed after taking prior permission from the manager • Gas cutting or welding work shall only be performed under the supervision of a safety officer or colliery engineer • Flashback arrester, sand, and water shall be provided near gas cutting or welding workplace
Contrabands	Chance of fire and explosion, injury to workers	L2	C3	9 Medium	• Body searcher shall be deployed • Awareness among workers shall be increased

Stone dust barrier not provided at panel entry	Chance of explosion	L4	C4	21 High	• Stone dust barriers shall be provided at panel entry
Accumulation of coal dust at working panel and loading points	fire and explosion	L3	C3	13 Medium	• Coal dust shall be cleaned regularly, by providing proper ventilation • Water spraying and stone dusting shall be performed as a preventive measure
Non-provision of fire stoppings where CH_4 exceeds 2%	Chance of explosion	L3	C5	22 High	• Fire stoppings shall be converted into explosion proof stoppings • Fire stoppings shall be inspected weekly once by a competent person • Gases shall be monitored continuously by Tele Monitoring System
Mine fire					
Susceptibility of spontaneous heating due to low Cross Point Temperature and high moisture content	Chance of fire, coal seam more susceptible to spontaneous heating	L4	C4	21 High	• Monitoring shall be performed to early detect fire • Panels shall be formed considering the incubation period of the coal so that the panel will finish before incubation period • Proper ventilation shall be provided
Shallow depth of cover	Leaking of air from the surface into sealed off areas, special heating	L4	C4	21 High	• No working shall be allowed beyond less than 15m hardcover line • The area demarcated in the underground shall be isolated by providing sectionalisation stoppings
Geological disturbance affecting panel	Chance of fire, coal seam more susceptible to spontaneous heating	L2	C4	14 Medium	• Adequate support as per SSR shall be provided near the disturbed area • Supports shall be monitored continuously • 15m barrier shall be left against fault plane • The environment at disturbed area shall be monitored regularly
Thick seam	Chance of fire	L3	C4	18 Medium	• Panels shall be formed considering the incubation period of the coal so that the panel will finish before incubation period • Remote control LHD shall be deployed for additional recovery of coal from the panel • Proper stowing shall be performed

Huge depillared area	Special heating	L3	C5	22 High	• Sub panels shall be prepared • Timely stowing shall be performed
Non-provision or poor firefighting arrangements	Uncontrolled fire, injury to workers	L3	C3	13 Medium	• All the firefighting equipment shall be provided and maintained properly • Periodic maintenance shall be carried out
Ventilation					
Inadequate ventilation	Chance of fire and risks associated with fire	L3	C4	18 Medium	• Permanent ventilation stopping shall be provided • Auxiliary fan shall be provided • Pressure quantity survey shall be carried out, and actions shall be taken accordingly • Mine workings shall be properly sectionalized • Return airway shall be cleaned regularly to reduce the resistance of the mine
Insufficient fan capacity	Inadequate ventilation of mine working, chance of fire and explosion	L3	C4	18 Medium	• Main mechanical ventilator fan of sufficient capacity with standby ventilator shall be installed • Each district shall be planned with separate intake and return airways • Complete sectionalisation of old and unused workings shall be performed
Non-availability or improper auxiliary fan	Accumulation of noxious gases, exposure of workers to the accumulated noxious gases, heat stroke, heat exhaustion, non-clearance of post-detonation fumes from working faces, spontaneous heating, chance of fire in old workings	L4	C3	17 Medium	• Auxiliary fans shall be maintained regularly • Sufficient number of auxiliary fans shall be provided • Proper coursing of air shall be performed using by temporary ventilation stopping
Obstruction or chocking of the return airway or insufficient intake	Inadequate ventilation, accumulation of gases, chance of fire and explosion	L3	C3	13 Medium	• Return airway shall be inspected regularly • Fallen coal or obstruction shall be removed regularly and completely • At least 2 intake airways in every district shall be maintained

Blind heading	Accumulation of noxious gases, exposure of workers to the accumulated noxious gases, heat stroke, heat exhaustion, non-clearance of post-detonation fumes from working faces, spontaneous heating, chance of fire in old workings	L4	C3	17 Medium	• Drivage of galleries shall be planned in a way to minimize blind heading • Auxiliary fan shall be installed for ventilation of blind heading • Proper coursing of air shall be performed using by temporary ventilation stopping • Sufficient number of coursing fans with flexible duct shall be provided
Heat and humidity	Heat stroke, work capacity reduces, collapse of workers, fatigue, vomiting, nausea, symptoms of shock, headache	L3	C3	13 Medium	• Working shall be performed in a panel system with an independent ventilation circuit • Double door connection between intake and return airway shall be provided • Spot coolers shall be provided • Drivage of gallery shall be restricted up to 5 headings (3 intake +2 return)
Lengthy ventilation route	Poor ventilation, heat and humidity leads to uncomfortable working conditions for workers	L3	C3	13 Medium	• Ventilation of the district shall be planned on the shortest route • Duct leakages shall be eliminated, and proper coursing shall be performed

4.4. Results and Discussion

In this study, with the aim of assessing the safety risks qualitatively in the mine-1, FMEA and WRAC techniques were applied. The results of the FMEA study are presented in Table 4.1. In the FMEA study, 14, 10, and 17 hazards were identified by analysing the mechanical components of the belt conveyor system, rope haulage system, and LHD respectively. Some of the components have the possibility of having two or more failure modes. For example, in the belt conveyor system, the component belt has four failure modes, i.e. "improper belt joining", "deteriorated belt", "fumes from the fire on the belt", and "loose belt". Out of 14 failure modes identified in the belt conveyor system, 1 hazard was related to work method/procedure, 10 were machine/tool-related hazards, and 3 were work environmental conditions related hazards. In rope haulage systems and LHD, all the failure modes identified were machine/tool-related hazards.

From Table 4.1, one can observe that most of the identified failure modes of the belt conveyor systems were having “drawing-in of the worker” and “generating frictional heat” as failure effects. “Unguarded idlers” have the highest risk level followed by “use of inflammable materials” among all the other hazards related to the belt conveyor system. Failure to control these hazards may lead to fatal or catastrophic consequences. “Runway of tubs” is the most common failure effect of various component failure in the rope haulage system. Though the failure of haulage components may not have a catastrophic consequence, they often lead to fatal or serious accidents in the underground mines. “Breakage of rope due to wear, rusting or improper splicing” has the highest risk level among the hazards related to rope haulage system. From Table 4.1, one can also observe that the “improper pilot switch” and “oil leakage” from the LHD engine can initiate a fire. Failure to control this effect may lead to catastrophic consequences. “Oil leakage” and “poor or damaged flexible trailing cable” have the highest risk level among the hazards related to LHD. Examination of the existing control measures revealed that “pre-start inspections”, “schedule inspections”, and “periodical maintenance” were adequate to reduce most of the failure effects of the belt conveyor system, rope haulage system, and LHD.

The results of the WRAC study are presented in Tables 4.2–4.9. In the WRAC analysis, 115 hazards related to ground movement (17), rope haulage system (16), belt conveyor (12), LHD (15), electricity (13), blasting (11), inundation (6), and dust, gas and other combustible materials (25) were identified. Associated risks of each hazard identified were enumerated in the WRAC template, and the identified hazards were ranked based on the likelihood and consequence of the individual hazard. Out of 115 hazards identified, 38 were workers’ action, 21 were work methods/procedural, 27 were machine/tool, and 29 were work environment/ managerial related hazards. From the results, it is evident that some of the hazards identified have multiple risks. For example, “geologically disturbed areas” has the chance of inundation, roof and side fall, and the chance of fire as risks and “presence of subsidence cracks and fissures on the surface above development panel” has the chance of fire and explosion, the chance of inundation, roof and side fall as risks.

In the WRAC study, to differentiate relative risks and to help in decision making, a 5×5-risk matrix was used. The hazards with the highest risk score and risk level should be given utmost priority among all the identified hazards to mitigate or minimize the risk level. The analysis of Tables 4.2–4.9 revealed that out of 115 hazards identified, 20 hazards had low-risk level, 86 hazards had medium-risk level, and 9 hazards had high-risk level. The hazards “blasting in a gassy seam” related to blasting operation, and “non-provision of fire stoppings where CH_4 exceeds 2%”, “huge depillared area” related to dust, gas and other combustible materials with risk score 22 should be given the top priority among the high-risk level hazards. The risk score 22 indicates that these hazards can happen once every 10 to 100 years and the consequences can lead to multiple fatalities. The next priority should be given to the other high-risk level hazards with risk score 21. They were “poor supervision”, “improper testing and dressing” related to the ground movement, “improper maintenance of flameproof features” related to the electricity, and “stone dust barrier not provided at panel entry”, “susceptibility of spontaneous heating due to low Cross Point Temperature and high moisture content”, “shallow depth of cover” related to dust gas and other combustible materials.

The purpose of qualitative risk assessment in the underground coal mines is to determine and prioritize the risk level of identified hazards so that the proper control measures can be implemented to eliminate or mitigate the risks to workers. This study has demonstrated that both the FMEA and WRAC techniques are competent at hazard identification, risk analysis, and risk evaluation in Indian underground coal mines. However, the risk evaluation techniques, i.e. rapid ranking method and 5×5-risk matrix employed in this study have few limitations as stated earlier.

As previous studies (Bowles & Peláez, 1995; Oraee et al., 2011; Shariati, 2014; Dallat et al., 2017) stated that the different values of probability, exposure, and consequence ratings may produce the same value of risk value, but their hidden risk implications may be very different. DGMS (2002) scales also produced the same risk values in some cases. For example, two different events with values of 1, 5, 3 and 5, 3, 1 for consequence, exposure, and probability respectively, have the same risk value of 15. In the former case, 1, 5, 3 implies one person can die due to frequent exposure to an unusual but possibly occurring hazard. In the latter case, 5, 3, 1 implies several persons can die due to seldom exposure to a conceivable but unlikely occurring hazard.

From the FMEA study (Table 4.1), one can observe that multiple failure modes have the same risk level. In the belt conveyor system, three failure modes, i.e. “unguarded tensioning arrangement”, “unguarded drive head”, “unguarded tail end” have the same risk level of 0.45 and two failure modes, i.e. “fumes from the fire on belt”, “loose belt” have the same risk level of 0.15. In the rope haulage system, two failure modes, i.e. “failure of drawbar”, “defective laying of track line” have the same risk level of 6 and two failure modes, i.e. “improper or defective clips or lashing chain”, “failure of sprags” have the same risk level of 4.5. In the LHD, two failure modes, i.e. “oil leakage”, “poor or damaged flexible trailing cable” have the same risk level of 1.8, three failure modes, i.e. “pilot switch not in order”, “temperature switch or cut-off valve not in order”, “improper reeling or unreeling” have the same risk level of 0.9. Four failure modes, i.e. “pressure relief valve not in order”, “head or rear light not working”, “audio-visual alarm or horn not working” “footswitch or dead-man switch not working” have the same risk level of 0.45, two failure modes, i.e. “bursting of tyre”, “improper gate-end box earthing” have the same risk level of 0.15. Two failure modes, i.e. “parking brake failure”, “service brake failure” have the same risk level of 0.04, and two failure modes, i.e. “improper condition of the bucket”, “dump valve not in order” have the same risk level of 0.002. From the above results, it is clear that it is hard to prioritize the failure modes with the same risk level using the rapid ranking method.

Similarly, from the WRAC study (Tables 4.2–4.9), one can also observe that multiple hazards have the same risk score and risk level. In the WRAC analysis of ground movement, 15 hazards have medium, and two have a high-risk level. Among the 15 medium-risk level hazards, three have 9, three have 10, two have 13, three have 17, and three have 18 as a risk score. The two high-risk level hazards, i.e. “poor supervision”, “improper testing and dressing” have an equal risk score of 21. In the WRAC analysis of rope haulage system, 13 hazards have low, and 3 have medium-risk level. Among the 13 low-risk level hazards, 11 have 5 as a risk score. Among the 3 medium-risk level hazards, two hazards, i.e. “lack of precaution while haulage track line crosses travelling road”, “non-provision of guards in haulage engine room” have an equal risk score of 8 and “failure of drawbar” has the highest risk score of 13. In the WRAC analysis of belt conveyor system, all the 12 hazards have medium-risk level. Among the 12 medium-risk level hazards, 8 have 13, and 4 have 18 as a risk score. In the WRAC analysis of LHD, all the 15 hazards have medium-risk level. Among the 15 medium-risk level hazards, 13 hazards have 13 as risk score. In the WRAC analysis of electricity, 12 hazards have medium-risk level. Among the 12 medium-risk level hazards, 2 have 10, and 9 have 13 as a risk score. In the WRAC analysis of blasting, 9 hazards have medium-risk level. Among the 9 medium-risk level hazards, 2 have 9, and 5 have 13 as a risk score. In the WRAC analysis of inundation, 5 hazards have low-risk level and 5 as a risk score. In the WRAC analysis of electricity, 12 hazards have medium-risk level. Among the 12 medium-risk level hazards, 2 have 10, and 9 have 13 as a risk score. In the WRAC analysis of dust, gas and other combustible materials, 19 hazards have medium, and 5 have high-risk level. Among the 19 medium-risk level hazards, 2 have 9, 2 have 10, 5 have 13, 3 have 14, 2 have 17, and 5 have 18 as risk score. Among the 5 high-risk level hazards, 3 have 21 as a risk score, and 2 hazards, i.e. "non-provision of fire stoppings where CH_4 exceeds 2%", "huge depillared area" have 22 as a risk score. From the above results, it is clear that it is hard to prioritize the hazards with the same risk level using the 5×5-risk matrix.

4.5. Quantitative Approaches

4.5.1. Fault Tree Analysis

FTA is typically useful when the logical structure of the causes of a major unwanted event is not immediately clear. The accident data collected from the mine-1 revealed that two fatal, nine serious accidents have occurred in the mine from 2001 to 2016. A typical accident report consists of the date, time, location, and place of the accident; age, designation, and experience of the victim; nature of injury; description and cause of the accident; conclusion, and enforcement actions. Out of nine serious accidents, the detail accident report of seven accidents was incomplete and not addressed the cause of the accident. Therefore, they were excluded from this study. Based on the review of the collected data, a database was developed as shown in Table 4.10. In this study, Logan Fault and Event Tree Analysis Version 7.2.7 software was used in constructing fault and event trees.

Table 4.10 Description of the accidents occurred in mine-1

Accident number	Date, time	Designation, age	Description of the accident
Fatal 1	23.06.2006 12.00 pm	Pump khalasi, 58 years	While a gang of ten persons including a pump khalasi were engaged for extension of suction pump in an old unsupported gallery that had recently been exposed from the water. A mass of coal measuring 4.8m×4.35m and having a thickness of 0.2-0.4m parted from the roof and fell on to the pump khalasi and a fitter from a height of 2.6m. The pump khalasi was trapped beneath the fallen coal, and the fitter was partially buried under the coal. Rest of the workers who were carrying out pipe assembling work further on the dip side of the site of the roof fall escaped unhurt.
Fatal 2	18.11.2011 8.30 pm	Chute operator	While a chute operator was loading tippers by standing near the operating panel located below the bunker, the

		25 years	conical shape hopper of the bunker dislodged from the welded joint with the main bunker and fell over the chute operator causing death.
Serious 1	06.01.2005 5.15 am	Explosive carrier 36 years	At 54LS/34D there was a layer of shale left in the roof that was to be taken. Attempts made to dress down the shale layer were failed. So, it was decided to bring it down by blasting. In this process, eight shot holes were drilled in the roof. The first four holes from the junction (outbye end of the face) were charged and blasted. The blast resulted in the fall of a layer in such a way that the second hole from the dip side of the gallery was destroyed /damaged, a layer of shale measuring about 1feet long remained on the rise side of the gallery, and one piece of shale measuring about 1.5feet remained on the dip side of the gallery. Attempts were made to dress down the same. However, with no positive result, it was decided to charge the remaining 3 holes. While charging the holes, the shale piece from the rise side suddenly was separated from the roof and side and fell on to the back of the injured explosive carrier who was standing nearer to the rise side of the pillar. The shale layer fell directly on to the explosive carrier's pelvis where cap lamp battery was attached to the body rubbing his back slightly. Due to this, the explosive carrier was thrown forward and fell on to the coal left over due to the previous blasting receiving out on his forehead.
Serious 2	26.11.2005 8.30 pm	Senior overman 54 years	At about 7.00 pm in the 2nd shift one of the tyre of LHD at 12LS district was got punctured. On getting the information from the Communication Dispatch System (CDS) operator, the shift in-charge enquired about the spare tyre. After some time, the shift in-charge was informed by the CDS operator that the spare tyre was not available in the underground, a tyre is at available at the surface, and minimum four persons will be required for taking the tyre. The shift in-charge directed a dresser and general mazdoor from 38LN district to bring the tyre from the surface along with two more workers who will accompany overman from 12LS district. The shift in-charge then instructed the overman of 12LS district to take two workers from his district to the surface and bring the tyre with the help of above four persons. The dresser and general mazdoor came to the surface and asked the CDS operator about the tyre. CDS operator gave then the tyre from the workshop. The dresser and general mazdoor took the tyre up to the mouth of the travelling drift and waited for another two persons. In the meantime, they started to tie the tyre with galvanized iron wire, so that when another two persons from underground reach they could take the tyre immediately. During that process, the tyre started rolling down. The rolling tyre hit the overman who was on the way to surface at the travelling drift.

4.5.1.1. FTA for fatal accident 1

The roof fall was taken as the TOP event for the accident. After that, the different reasons that may cause the top event to occur was studied and analysed. The top event was broken up into two intermediate events. These intermediate events were further broken up to identify the root causes of the accident. Based on the causes mentioned in the accident report, the fault tree was constructed as shown in Figure 4.1.

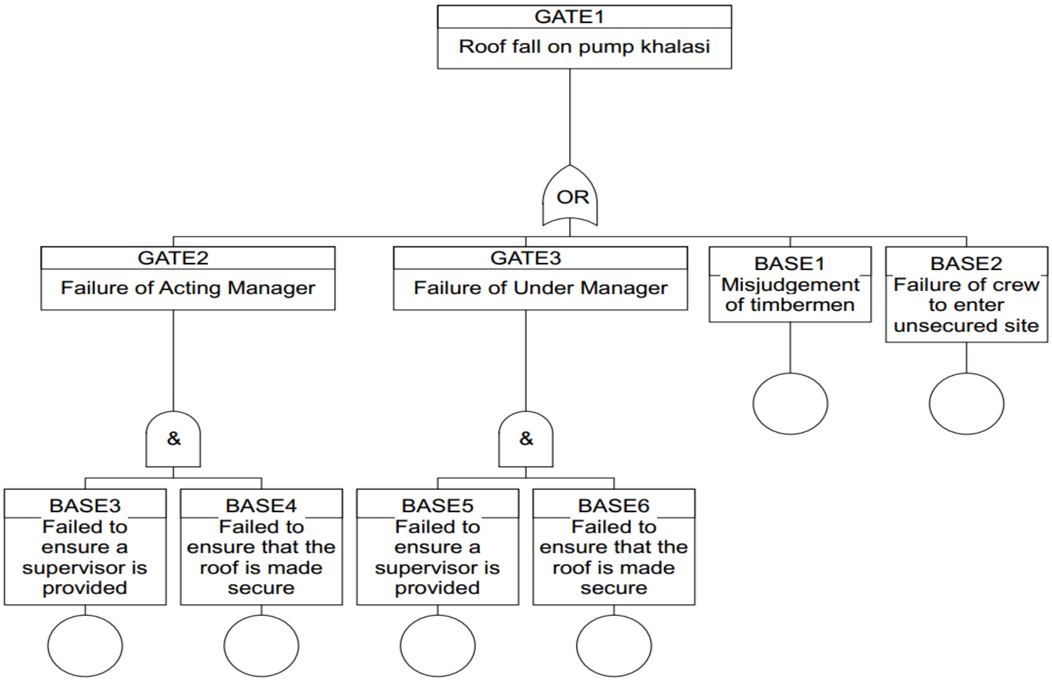


Figure 4.1 Fault tree of roof fall on pump khalasi

Cut sets, Gate1 = Gate2 + Gate3 + Base1 + Base2

= (Base3 · Base4) + (Base5 · Base6) + Base1 + Base2

Cut sets = {Base1}, {Base2}, {Base3, Base4}

Minimal cut sets = {Base1}, {Base2}

4.5.1.2. FTA for fatal accident 2

The fall of CHP bunker was taken as the TOP event for the accident. After that, the different reasons that may cause the top event to occur was studied and analysed. The top event was broken up into four intermediate events. These intermediate events were further broken up to identify the root causes of the accident. Based on the causes mentioned in the accident report, the fault tree was constructed as shown in Figure 4.2.

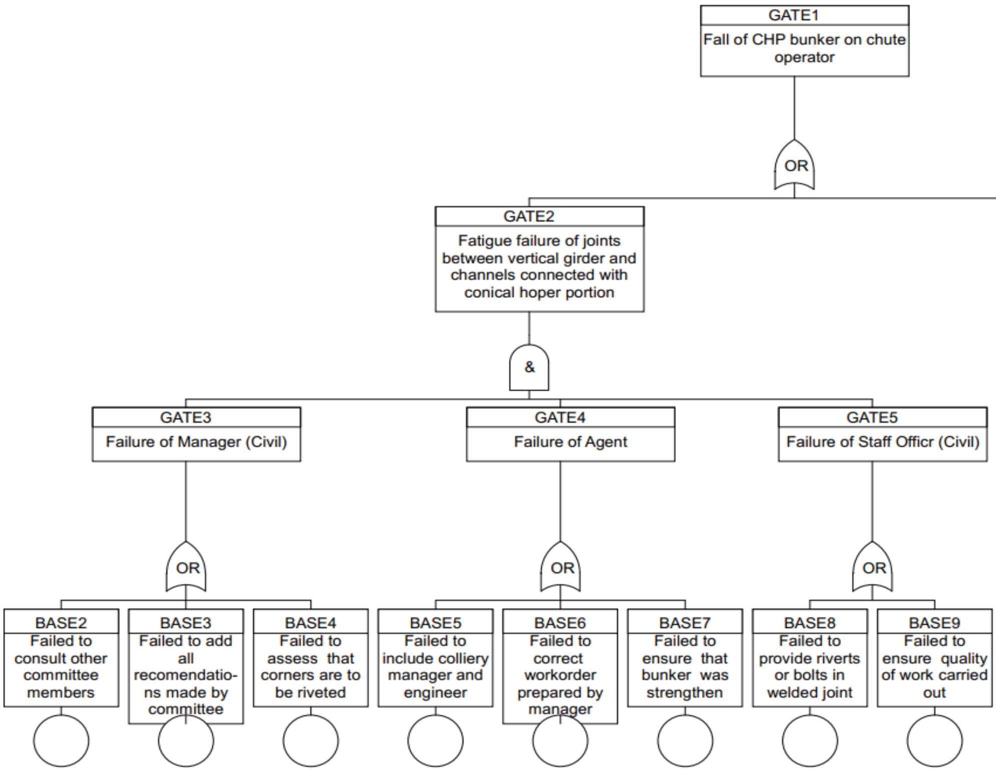


Figure 4.2 Fault tree of fall of CHP bunker

Cut sets, Gate1 = Gate2 + Base1

= (Gate3 · Gate4 · Gate5) + Base1

= ((Base2 + Base3 + Base4) · (Base5 + Base6 + Base7) · (Base8 + Base9)) + Base1

= Base2 · Base5 · Base8 + Base2 · Base6 · Base8 + Base2 · Base7 · Base8 + Base3 · Base5 · Base8 + Base3 · Base6 · Base8 + Base3 · Base7 · Base8 + Base4 · Base5 · Base8 + Base4 · Base6 · Base8 + Base4 · Base7 · Base8 + Base2 · Base5 · Base9 + Base2 · Base6 · Base9 + Base2 · Base7 · Base9 + Base3 · Base5 · Base9 + Base3 · Base6 · Base9 + Base3 · Base7 · Base9 + Base4 · Base5 · Base9 + Base4 · Base6 · Base9 + Base4 · Base7 · Base9 + Base1

Cut sets = {Base1}, {Base2, Base5, Base8}, {Base2, Base6, Base8}, {Base2, Base7, Base8}, {Base3, Base5, Base8}, {Base3, Base6, Base8}, {Base3, Base7, Base8}, {Base4, Base5, Base8}, {Base4, Base6, Base8}, {Base4, Base7, Base8}, {Base2, Base5, Base9}, {Base2, Base6, Base9}, {Base2, Base7, Base9}, {Base3, Base5, Base9}, {Base3, Base6, Base9}, {Base3, Base7, Base9}, {Base4, Base5, Base9}, {Base4, Base6, Base9}, {Base4, Base7, Base9}

Minimal cut sets = {Base1}

4.5.1.3. FTA for serious accident 1

The roof fall on an explosive carrier was taken as the TOP event for the accident. After that, the different reasons that may cause the top event to occur was studied and analysed. The top event was broken up into three intermediate events. These intermediate events were further broken up to identify the root causes of the accident. Based on the causes mentioned in the accident report, the fault tree was constructed as shown in Figure 4.3.

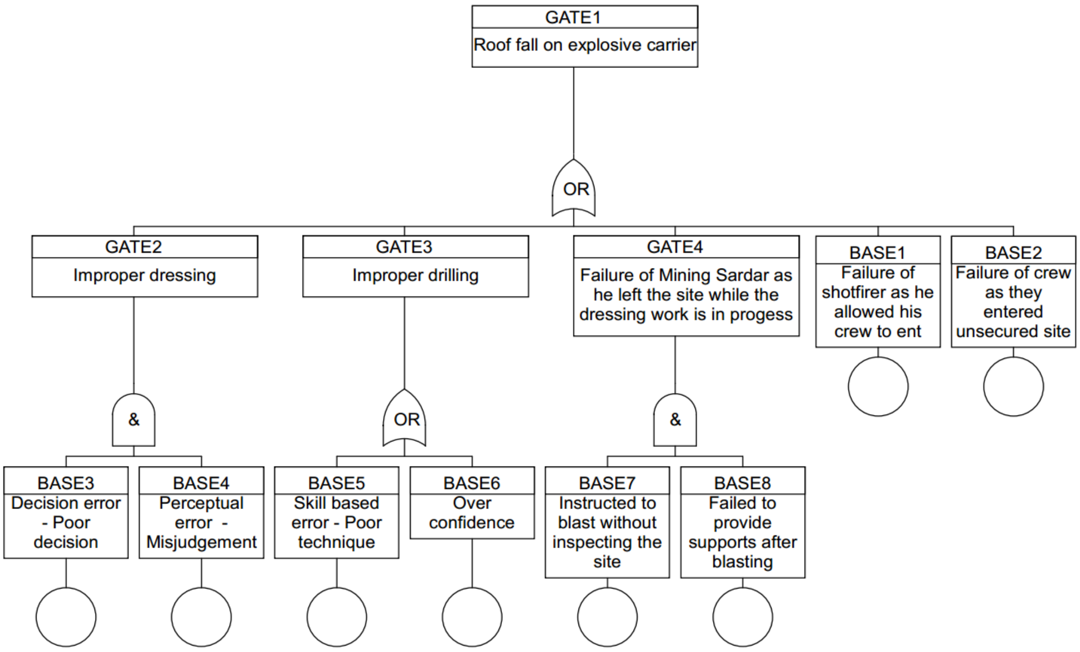


Figure 4.3 Fault tree of roof fall on explosive carrier

Cut sets, Gate1 = Gate2 + Gate3 + Gate4 + Base1 + Base2

$$= (\text{Base3} \cdot \text{Base4}) + (\text{Base5} + \text{Base6}) + (\text{Base7} \cdot \text{Base8}) + \text{Base1} + \text{Base2}$$

Cut sets = {Base1}, {Base2}, {Base5}, {Base6}, {Base3, Base4}, {Base7, Base8}

Minimal cut sets = {Base1}, {Base2}, {Base5}, {Base6}

4.5.1.4. FTA for serious accident 2

The rolling of LHD tyre accident was taken as the TOP event for the accident. After that, the different reasons that may cause the top event to occur was studied and analysed. The top event was broken up into an intermediate event. This intermediate event was further broken up to identify the root causes of the accident. Based on the causes mentioned in the accident report, the fault tree was constructed as shown in Figure 4.4.

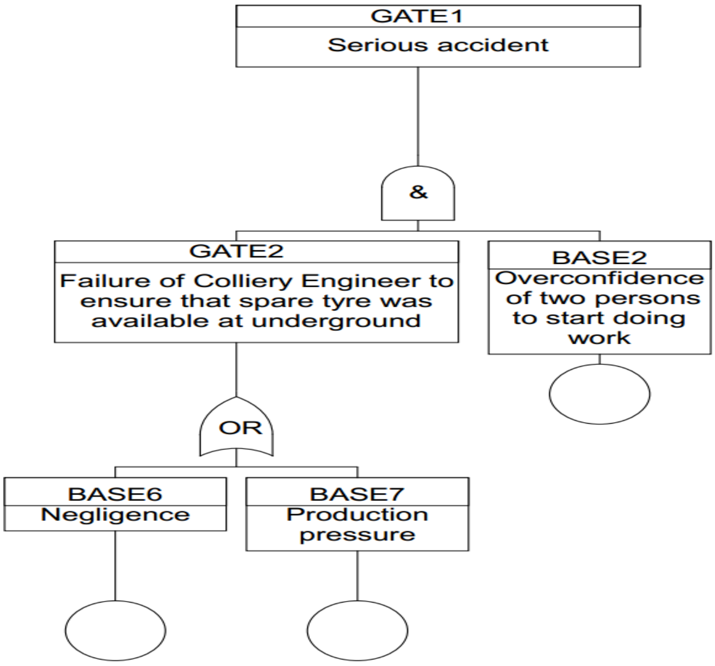


Figure 4.4 Fault tree of rolling of LHD tyre accident

Cut sets, Gate1 = Gate2 · Base2

= (Base6 + Base7) · Base2

= (Base6 · Base2) + (Base7 · Base2)

Minimal cut sets = {Base6, Base2}, {Base7, Base2}

4.5.2. Event Tree Analysis

An ETA is useful in identifying the various possible outcomes of a single hazardous event. From the accident data collected from mine-1, many hazardous events were identified. The event trees constructed for few hazardous events like roof fall due to improper roof dressing, fire in belt conveyor, breakage of haulage rope, and inundation due to barrier thickness failure are presented in Figures 4.5-4.8 respectively.

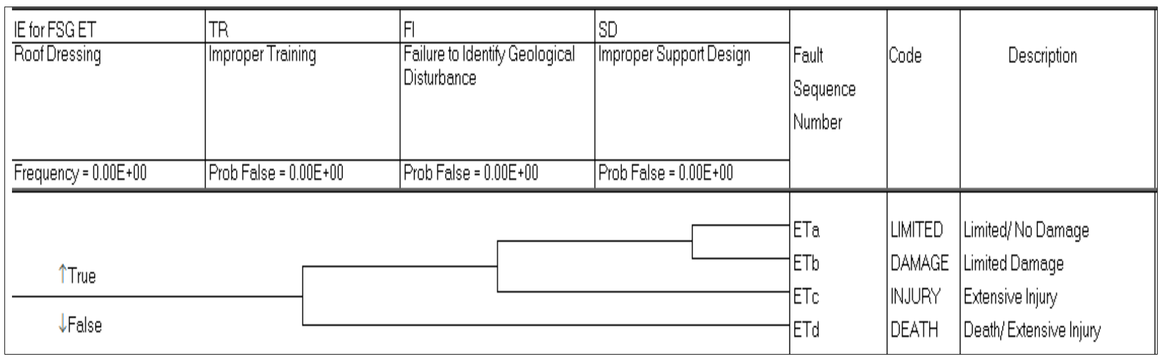


Figure 4.5 Event tree for roof fall due to roof dressing

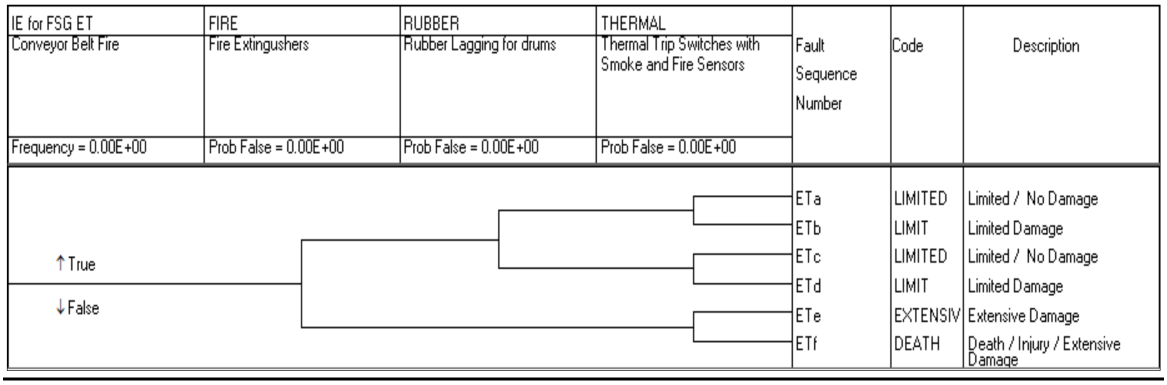


Figure 4.6 Event tree for the conveyor belt fire

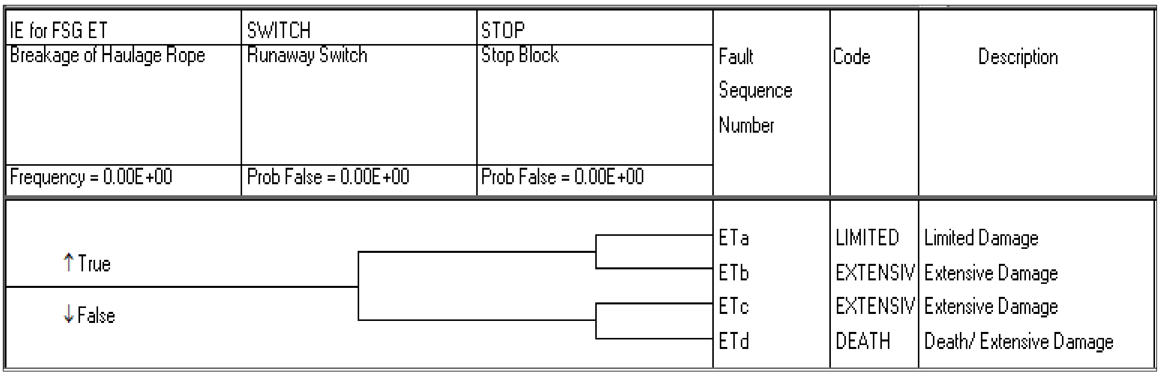


Figure 4.7 Event tree for breakage of haulage rope

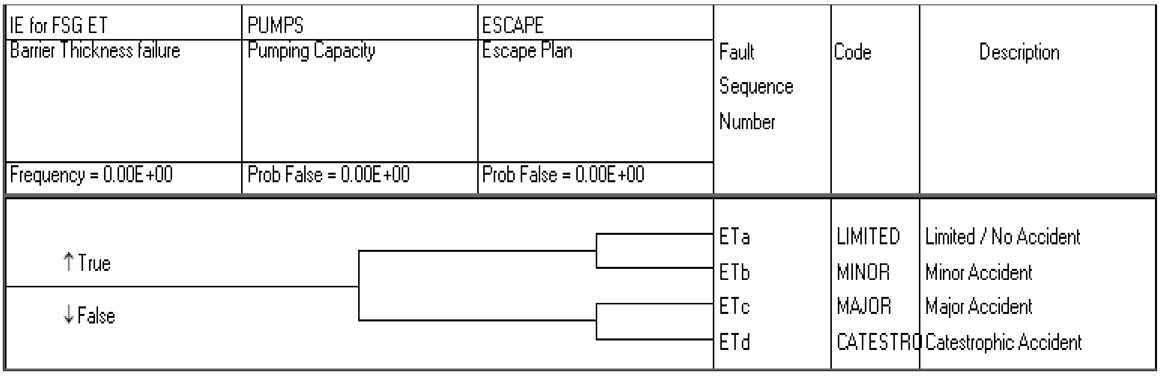


Figure 4.8 Event tree for inundation due to barrier thickness failure

4.6. Results and Discussion

In this study, with the aim of assessing the safety risks quantitatively in the mine-1, FTA and ETA techniques were applied. Fault trees were constructed by stepping through a series of events logically to determine the causes of failure of the initiating events. The constructed fault trees for the accidents were represented in Figures 4.1 to 4.4. Figure 4.1 was constructed based on the report of fatal accident 1. From the Figure 4.1, it is clear that the fatal accident, i.e. "roof fall on pump khalasi" could have been averted if "timberman has supported the roof", "the crew would not have entered the unsecured site", or "a supervisor was provided to ensure that the roof was made secure before allowing the crew to enter the worksite**".**

Figure 4.2 was constructed based on the report of fatal accident 2. From the Figure 4.2, it is clear that the fatal accident, i.e. "fall of CHP bunker on chute operator" could have been averted if "the operator room was provided away from the bunker", "manager (civil) has consulted other committee members", "manager (civil) has added all recommendations made by the committee", "manager (civil) has assessed that hopper corners are to be riveted", "agent has included colliery manager and engineer in the committee", "agent has corrected the work order prepared by the manager (civil)", "agent has corrected the work order prepared by the manager (civil)", "agent has ensured that the bunker was strengthened", "staff officer (civil) has provided rivets or bolts in welded joints", or "staff officer (civil) has the quality of previous work carried out to strengthen the bunker". The minimum path with which this accident could have been prevented is by "providing the operator room away from the bunker".

Figure 4.3 was constructed based on the report of serious accident 1. From the Figure 4.3, it is clear that the serious accident, i.e. "roof fall on an explosive carrier" could have been averted if "shotfirer had not allowed his crew to enter unsecured site", "crew had not entered unsecured site", "properly dressed the roof by support crew", "properly drilled the holes by blasting crew", "mining sirdar had inspected the site before allowing blast operation", and "mining sirdar had instructed to support the roof after the blast". Figure 4.4 was constructed based on the report of serious accident 2. From the Figure 4.4, it is clear that the serious accident, i.e. "rolling tyre" could have been averted if "the general mazdoor and dresser had waited for the two more persons before starting the work", "spare tyre was made available at underground by the colliery engineer".

Event trees were constructed to determine the possible outcomes of an initiating event. From the Figure 4.5, it is evident that the initiating event, i.e. "improper roof dressing" with subsequent events "improper training", "failure to identify geological disturbance", "improper support design" have the following consequences "no damage", "limited damage", "extensive injury", and "death". From the Figure 4.6, it is evident that the initiating event, i.e. "fire in belt conveyor" with subsequent events "fire extinguishers", "rubber lagging for drums", "thermal trip switch with smoke and fire sensors" have the following consequences "no damage", "limited damage", "extensive injury", and "death".

From the Figure 4.7, it is evident that the initiating event, i.e. "breakage of rope haulage" with subsequent events "runaway switch", "stop block" have the following consequences "limited damage", "extensive injury", and "death". From the Figure 4.8, it is evident that the initiating event, i.e. "barrier thickness failure" with subsequent events "pump capacity", "escape plan" have the following consequences "no accident", "minor accident", "major accident", and "catastrophic accident".

The objective of FTA is to qualitatively identify the potential causes and pathways to a top event or quantitatively calculate the probability of the top event. The examination of root causes of the fatal and serious accidents considered in FTA study showed that only workers' actions were cited as the cause of all the accidents. Other hazards like procedural or work environment were not considered while conducting the accident investigation. Consequently, only workers' actions were presented as root causes for all the accidents in the FTA study. As is hard to maintain quantitative data on workers' action, the probability data for the workers' action was not available in mines. Therefore, from the application of FTA in an Indian underground coal mine, it can be concluded that only qualitative analysis can be performed in the Indian underground coal mines.

The purpose of ETA is to qualitatively identify the potential scenarios and sequences of events following an initiating event or quantitatively calculate the probability of the top event based on subsequent events. The application of ETA in an Indian underground coal mine revealed that only qualitative analysis could be performed in the Indian underground coal mines due to the lack of probability data of various subsequent events. The study also revealed that due to the presence of a large number of initiating events in the underground mines, it is hard to construct event tree for every initiating event. For example, 115 potential initiating events were identified from the WRAC study; to develop event trees for all the 115 initiating events is difficult and time-consuming.

4.7. Chapter Summary

In this chapter, the analysis and results of FMEA, WRAC, FTA and ETA techniques applied to mine-1 were presented. The applicability of these techniques to Indian underground coal mines was also discussed. From the analysis of the FMEA and WRAC results, few limitations were observed in the currently employed risk evaluation techniques, i.e. rapid ranking method and 5×5-risk matrix in the Indian mining industry. The inference of the findings of the FTA and ETA analysis were also discussed. From the analysis of the FTA and ETA results, it was noted that quantitative risk assessment could not be performed in Indian underground coal mines in the existing circumstances.

CHAPTER 5

PROPOSED METHODOLOGY FOR SAFETY RISK ASSESSMENT IN UNDERGROUND COAL MINES

5.1. Introduction

The application of risk assessment approaches in the mine-1 revealed that it is hard to prioritize the hazards using qualitative techniques, and quantitative techniques are not suitable for the Indian underground coal mines. Therefore, the proposed methodology was applied to evaluate the safety risks in underground coal mines. In this chapter, the details of the application of the proposed methodology to six underground coal mines (mine-1, mine-2, mine-3, mine-4, mine-5, and mine-6) and their results are presented.

5.2. Development of the Proposed Methodology

The proposed risk assessment methodology comprised of the following stages as represented in Figure 3.6:

- Preliminary stage
- Design stage
- Fuzzy logic – risk estimation stage
- VIKOR – risk prioritization stage
- AHP – risk estimation stage

5.2.1. Preliminary stage

The steps involved in the preliminary stage are context establishment, data collection and analysis, and hazard identification.

5.2.1.1. Establish context

In this study, the aim of the risk assessment was set to assess the safety risk of an underground mine using the proposed methodology. Therefore, underground mine was indicated at the mine level. The hazard factors associated with the underground mine were categorized as hazardous group level, and the hazards associated with the hazard factors were categorized as hazardous event level.

5.2.1.2. Data collection and analysis

The data collection was started with the aim of gaining knowledge on the type of accidents and incidents occurred over the years in Indian mines. In this study, data collection was carried out through the collection of accidents reports from DGMS and CIL subsidiary mine headquarters, and workplace observations during mine visits.

The accident data were collected from 2001 to 2015, from the DGMS and CIL subsidiary mines. The collected accident statistics contained the following details: name of the mine, owner, place of accident, brief cause of the accident, date of the accident, time of the accident, number of persons died, and number of persons seriously injured. Over 7500 incidents were observed over the study period. The mine-1 was also visited for data collection and observations. The observations in the mine were carried out using the DGMS (2015) cause-wise accident classification and ILO (ILO, 1994) mines safety checklists that describe the details to be observed in each district of the mine.

5.2.1.3. Hazard identification

The analysis of the collected statistics revealed that 1609 fatal and 4973 serious accidents have occurred between 2001 and 2015. The cause-wise analysis of these fatal and serious accidents is shown in Figure 5.1. In this study, the causes classified by DGMS (2015), i.e. ground movement, transportation machinery (non-winding), machinery other than transportation machinery, explosives, electricity, other causes (inundation), and dust, gas and other combustible materials were considered as hazard factors and the hazards associated with these hazard factors were considered as hazard events. The hazard events of these hazard factors were identified from the analysis of accident data collected, review of checklists and safety audits present in the mine, and from the hazards identified in WRAC and FMEA analysis performed in chapter 4. A safety hazard database was created to store the hazard events and hazard groups. Specific hazards identified from the literature and after meeting with the mine personnel were also added to the hazard database.

5.2.2. Design stage

The steps involved in the design stage are as follows:

- Development of risk tree into hazardous group and event level,
- Collection of expert’s opinion for risk parameters,
- Development of MFs of P, E, C and RL, and

- Establishment of a rule base.

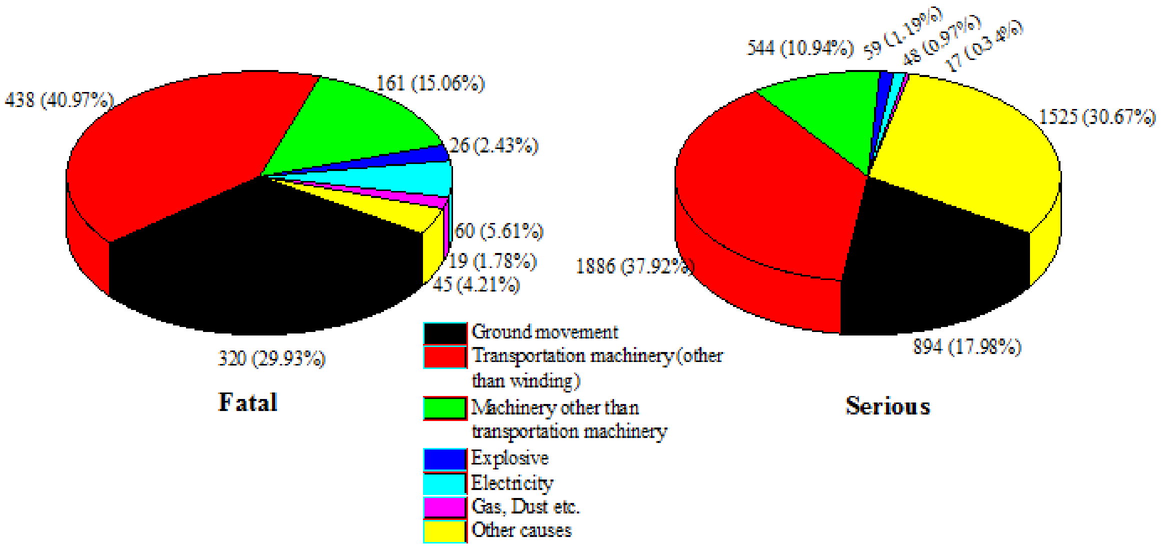


Figure 5.1 Cause-wise analysis of fatal and serious accidents in coal mines from 2001 to 2015

5.2.2.1. Development of risk tree into hazardous group and event level

In the hazard identification step, seven hazard groups and 177 hazard events were identified. A risk tree was developed from the identified hazards for effective risk analysis in the mine as shown in Figure 5.2.

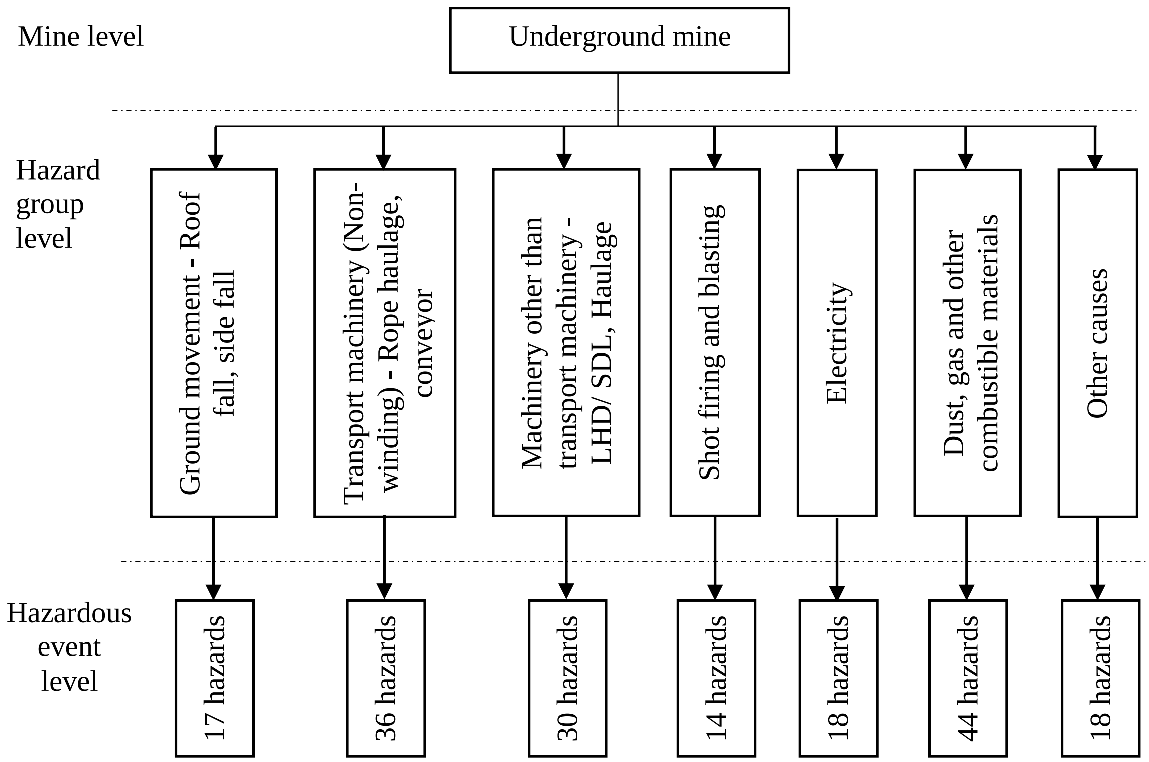


Figure 5.2 Hazard identification at different levels for an underground coal mine

5.2.2.2. Collection of experts' opinion

The collected accident data was defined subjectively, the descriptive terms were vague and imprecise, and the risk parameters data for the identified hazards were not available. Therefore, questionnaires were developed to collect the risk parameters data and relative importance. The questionnaires were developed for all the hazard events and hazard groups as shown in Appendix A and Appendix B. In this study, the judgment of experienced safety experts' in the six underground coal mines (mine-1, mine-2, mine-3, mine-4, mine-5, and mine-6) was recorded using the survey questionnaires designed.

5.2.2.2.1. Questionnaire design

The questionnaires in Appendix A were developed based on the retrospective study design. The questionnaires were developed based on guidelines presented by Burgess (2001) and Kothari (2004). The hazard groups, i.e. geo-mechanical (ground movement), mechanical (rope haulage system, belt conveyor system, LHD/SDL), chemical (shot firing and blasting), electrical (electricity), geochemical (dust, gas and other combustible materials), environmental (inundation) and the hazard events related to human, machine/tool, work methods/procedural, and work environment/managerial hazards were included in the questionnaires. All the questionnaires consisted of qualitative type questions and three risk parameters. The measurement type of the three risk parameters, i.e. consequence, exposure, and probability is "Discrete". A six-point Likert scale was used to record the responses of the respondent workers to the questionnaire. The scale values and the expected responses are shown in Table 5.1. A pairwise comparison of risk parameters was also included in the questionnaires to collect the weights of the risk parameters.

The questionnaire in Appendix B is a pairwise comparison matrix of hazard factors. In this questionnaire, the respondents were asked to compare the importance of one hazard factor with all the other hazard factors using the Saaty's AHP scales presented in Table 3.6. For example, in the first row of questionnaire, the respondents were asked to compare the "Ground movement (fall of roof/side)" with "Transport machinery (rope haulage, conveyor)" and asked which criterion with the AHP priorities is more important and how much more on the scale of 1 to 9. A DGMS official vetted the questionnaires developed in this study.

Table 5.1 A six-point scales for indicator responses

Probability		Exposure		Consequence	
Scale values	**Linguistic scale (Description)**	**Scale values**	**Linguistic scale (Description)**	**Scale values**	**Linguistic scale (Description)**
P1	Practically impossible (One in 1000 years)	E1	Very rare (More than yearly)	C1	Small injury (Minor first aid)
P2	Conceivable but possible (Once every 100 years)	E2	Rare (Yearly)	C2	Minor (Temporary disability, many lost time injuries)
P3	Only remotely possible (Once every thirty years)	E3	Unusual (Monthly)	C3	Serious (Significant chance of fatality, permanent disability)
P4	Unusual but possible (Once every ten years)	E4	Occasional (Weekly)	C4	Fatality (One fatality)
P5	Quite possible (Once every three years)	E5	Frequent (Daily)	C5	Major fatality (A few fatalities, 1-4 fatalities)
P6	May well be expected (Once a year)	E6	Continuous (Several times daily)	C6	Catastrophic (Many fatalities, > 4 fatalities)

5.2.2.3. Development of membership functions and rule base of risk parameters

The rating scales of P, E, C, and RL were developed for risk analysis by modifying the DGMS risk score (DGMS, 2002) and risk matrix (Sabir et al., 2012) used by CIL. Table 5.2 and Table 5.3 presents the linguistic scales and the corresponding fuzzy set value of P, E, C, and RL respectively. The triangular MFs were used in this study to represent the linguistic scales of input and output parameters as shown in Figure 5.3. The triangular MFs were developed based on the expert's judgement. Figure 5.3 is the pictorial representation of the linguistic scales and fuzzy sets of probability, exposure, consequence and risk level. In the figure, linguistic scales of the risk parameters are shown at the top of the triangles. The triangle starts at the lower range and ends at the highest range of the fuzzy set of the corresponding probability, exposure, consequence and risk level values.

Table 5.2 Rating scale for risk parameters of an event

Probability		Exposure		Consequence	
Linguistic scale	**Parameters of MFs**	**Linguistic scale**	**Parameters of MFs**	**Linguistic scale**	**Parameters of MFs**
P1	(0, 1, 2)	E1	(0, 1, 2)	C1	(0, 0.5, 1)
P2	(1, 2, 4)	E2	(1, 2, 4)	C2	(0.5, 1, 2)
P3	(2, 4, 6)	E3	(2, 4, 6)	C3	(1, 2, 3)
P4	(4, 6, 8)	E4	(4, 6, 8)	C4	(2, 3, 4)
P5	(6, 8, 10)	E5	(6, 8, 10)	C5	(3, 4, 5)
P6	(8, 10, 12)	E6	(8, 10, 12)	C6	(4, 5, 6)

Table 5.3 Rating scale for risk level of an event

Linguistic scale	Parameters of MFs
Low	(0, 10, 20)
Medium	(20, 110, 200)
High	(200, 500, 700)

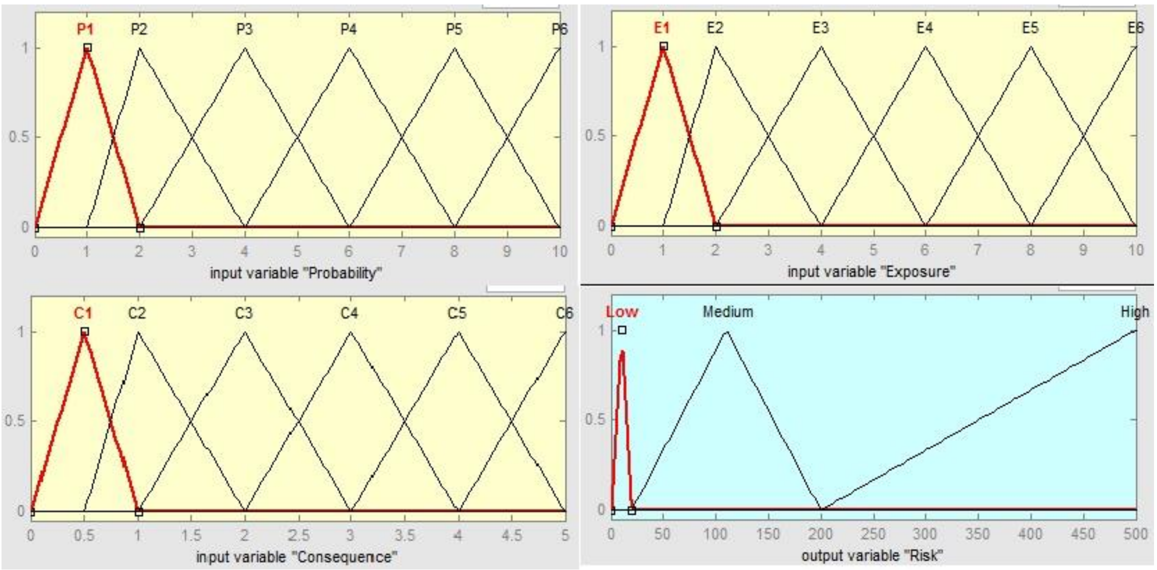


Figure 5.3 The membership functions of probability, exposure, consequence and risk level

Because there were six linguistic scales for three risk parameters, the rule base consisted of 216 (6×6×6) IF-THEN rules. The fuzzy rule base is presented in Appendix C. The first rule of Appendix C would be represented as below:

If P is 'Practically impossible' and E is 'Very Rare' and C is 'Small injury', Then RL is 'Low'

5.2.3. Graphical User Interface

The steps involved in the next stages of the proposed methodology are risk estimation of hazard events using fuzzy logic, risk prioritization of the hazard events using VIKOR, risk estimation of hazard groups using AHP, and evaluating the overall mine risk level. The manual evaluation of risk level using these stages of the proposed methodology requires many man-hours. Therefore, to reduce the calculation time significantly and to increase the speed of the risk assessment process, a GUI was developed. The GUI is referred to as Tool for Risk Assessment in Mines (TRAM). The algorithm of TRAM is represented in Figure 5.4.

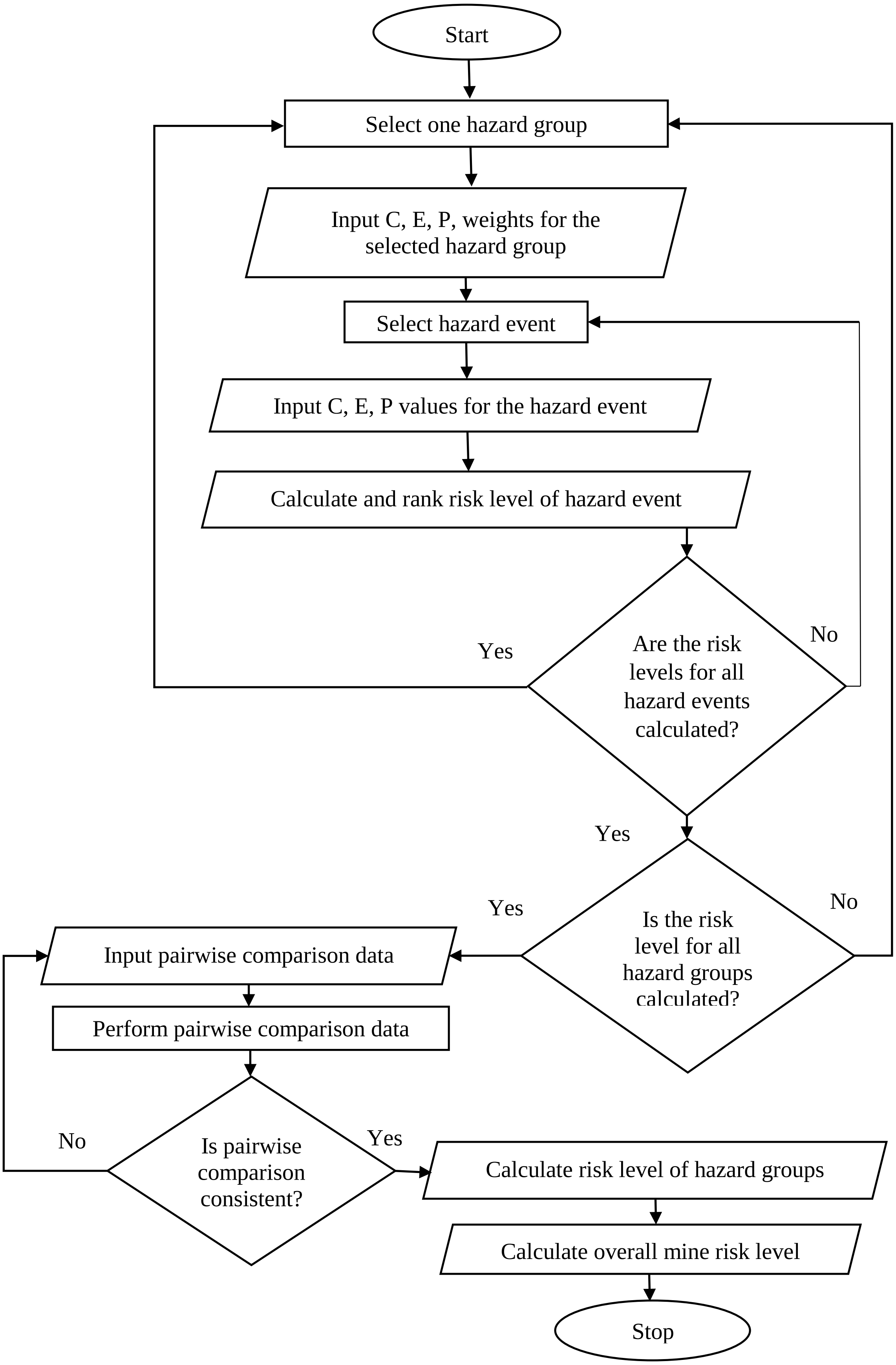


Figure 5.4 Algorithm of TRAM

5.2.3.1. TRAM architecture design

The TRAM is aimed to help the mining risk assessment process through a user-friendly interface, hence requiring no prior knowledge of the proposed methodology. The GUI of TRAM was coded using the C# language through Microsoft Visual Studio 2015 and .Net libraries (Microsoft Docs, 2017). TRAM runs on a Microsoft Windows 7 or higher platform within a .Net 4.0 framework.

TRAM consists of the following main modules: Database layer, Logic layer, User interface. The one tier architecture of the TRAM is presented in Figure 5.5.

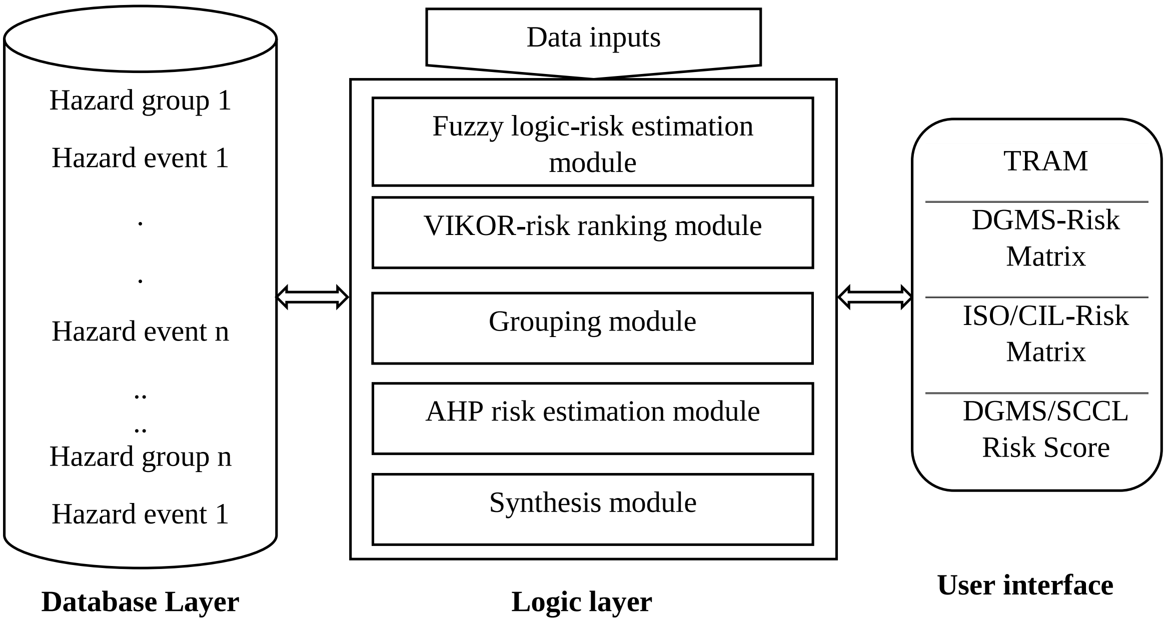


Figure 5.5 Architecture of TRAM

5.2.3.2. Database layer

The hazard groups and their associated hazard events identified from the collected data were set up in a pre-defined format, which can be retrieved and used for risk analysis study. As the XML file format (w3schools, 2006) is portable and simplifies data sharing, data availability, data transport and platform changes, the data was stored in XML files. Seven types of hazard groups and their associated 177 hazard events were incorporated in the overall database. The details of the type of hazard groups and events that were incorporated in the database were presented in Appendix A. As hazard identification is a continuous process, the hazards list can be updated whenever necessary. To facilitate the modifications/updates of the database, at any stage of the risk analysis process, an ‘Admin Tab’ was provided.

5.2.3.3. Logic layer

The logic layer comprised of four modules to perform the risk analysis process and to manage data. Fuzzy variables, triangular membership functions for C, E, P, and Risk Level (Figure 5.3), and the rule base in the fuzzy logic-risk estimation module were developed based on the proposed methodology to compute the risk levels of hazard events at the event level. Fuzzy logic-risk estimation module was designed to fuzzify and defuzzify the risk parameters based on the fuzzy rules developed (Appendix C). A snippet of fuzzy logic is presented in Figure 5.6.

```
        // Create new fuzzy system
 if (_fsRank == null)
 {
   _fsRank = CreateSystem();
   if (_fsRank == null)
   {
     return;
   }
 }
   // Get variables from the system (for convinience only)
   FuzzyVariable fvProbability = _fsRank.InputByName("probability");
   FuzzyVariable fvExposure = _fsRank.InputByName("exposure");
   FuzzyVariable fvConsequence = _fsRank.InputByName("consequence");
   FuzzyVariable fvRisk = _fsRank.OutputByName("risk");

   // Associate input values with input variables
        Dictionary<FuzzyVariable, double> inputValues =
                                    new Dictionary<FuzzyVariable, double>();
   inputValues.Add(fvProbability, (double)nudInputProbability.Value);
   inputValues.Add(fvExposure, (double)nudInputExposure.Value);
   inputValues.Add(fvConsequence, (double)nudInputConsequence.Value);

   // Calculate result: one output value for each output variable
  Dictionary<FuzzyVariable, double> result = _fsRank.Calculate(inputValues);
```

Figure 5.6 A snippet of fuzzy logic

VIKOR-risk ranking module was developed based on the Opricovic (1998) which was designed to develop a ranking solution which will have the maximum group utility and the minimum individual regret of the opponent. The grouping module manages the data and presents the results at the event level. The evaluated hazard events were stored in a data grid view. Based on the fuzzy logic method, the evaluated hazard events were categorized as low (green colour), medium (yellow colour) and high (red colour) and based on the VIKOR method, the evaluated hazard events were arranged dynamically in the descending order of ranks obtained. A snippet of VIKOR ranking method is presented in Figure 5.7.

The AHP risk estimation module was developed based on the Saaty's (1990) work which was designed to determine the weights of the hazard groups. The synthesis module was designed to ensure that the risk analysis is performed from the event level to group level and finally to overall mine level. A snippet of the AHP method is presented in Figure 5.8.

```
    //Calculate VIKOR-SQR Values
    pMin = eMin = cMin = 13;
    pMax = eMax = cMax = -1;
        calculateEventRanking = true;
    double sValue = 0;
    double rValue = 0;
    double tempVal1, tempVal2, tempVal3;
    foreach (string hazardEvent in list)
    {
        RiskTableRow rowData = riskTableData[hazardEvent];
sValue = rValue = tempVal1 = (pWeight * (pMin - rowData.Probability) / (pMin - pMax));
        tempVal2 = (eWeight * (eMin - rowData.Exposure) / (eMin - eMax));
        if (tempVal2 > rValue)
        {
            rValue = tempVal2;
        }
        sValue += tempVal2;
        tempVal3 = (cWeight * (cMin - rowData.Consequence) / (cMin - cMax));

        if (tempVal3 > rValue)
        {
            rValue = tempVal3;
        }
        sValue += tempVal3;
   sValues.Add(hazardEvent, sValue);      rValues.Add(hazardEvent, rValue);
       riskTableData[hazardEvent].S = sValue;   riskTableData[hazardEvent].R = rValue;

        if (double.IsNaN(sValue) || double.IsNaN(rValue))
        {
            calculateEventRanking = false;
        }
    }
    sMax = sValues.Values.Max();
    rMax = rValues.Values.Max();
    sMin = sValues.Values.Min();
    rMin = rValues.Values.Min();

    double sDiff = sMax - sMin;
    double rDiff = rMax - rMin;
    foreach (string hazardEvent in list)
    {
     double qValue = 0.5 * (((sValues[hazardEvent] - sMin) / sDiff) + ((rValues[hazardEvent] - rMin)
/ rDiff));
        qValues.Add(hazardEvent, qValue);
        riskTableData[hazardEvent].Q = qValue;
        if (double.IsNaN(qValue))
        {
            calculateEventRanking = false;
        }
    }
}
```

Figure 5.7 A snippet of VIKOR ranking method

```
      {
        double[] rowAvg = new double[listHazardNames.Count];
        double[] colSum = new double[listHazardNames.Count];
        double[][] divisionMatrix = new double[listHazardNames.Count][];
        double lambdaMax = 0;
        double[] randomIndex = { 0, 0, 0.58, 0.9, 1.12, 1.24, 1.32, 1.41, 1.45, 1.49 };
        for (int col = 0; col < listHazardNames.Count; col++)
        {
          colSum[col] = 0;
          for (int row = 0; row < listHazardNames.Count; row++)
          {
            colSum[col] += ahpMatrix[row][col];
          }          }
        for (int row = 0; row < listHazardNames.Count; row++)
        {
          double rowSum = 0;
          divisionMatrix[row] = new double[listHazardNames.Count];
          for (int col = 0; col < listHazardNames.Count; col++)
          {
            divisionMatrix[row][col] = ahpMatrix[row][col] / colSum[col];
            rowSum += divisionMatrix[row][col];
          }
          rowAvg[row] = rowSum / listHazardNames.Count;
          lambdaMax += (rowAvg[row] * colSum[row]);
        }
double consistencyIndex = (lambdaMax - listHazardNames.Count)/(listHazardNames.Count- 1);
double consistencyRatio = consistencyIndex / randomIndex[listHazardNames.Count];
        if (consistencyRatio < 0.1)
        {
        Dictionary<string, double> groupRisk = new Dictionary<string, double>();
          foreach (IGrouping<string, string> hazardGroup in query)
          {
            int index = hazardGroup.Key[0] - 49;
            List<string> hazardNames = hazardGroup.ToList<string>();
            double sum = 0;
            foreach (string name in hazardNames)
            {
              sum += riskTableData[name].Risk;
            }
            groupRisk.Add(hazardGroup.Key, sum * rowAvg[index]);
          }
          var bs = new BindingSource();
          bs.DataSource = groupRisk;
          AHPgridTable.DataSource = null;
          AHPgridTable.DataSource = bs;
          DisplayAHPTable();                        }
        else
{MessageBox.Show(String.Format("Consistency Ratio = {0}.{1}Please revise the judgement.",
Math.Round(consistencyRatio, 3), System.Environment.NewLine), "Consistency Ratio",
MessageBoxButtons.OK, MessageBoxIcon.Error);
        }         }
```

Figure 5.8 A snippet of the AHP method

5.2.3.4. User interface

The user interface offers the user with a user-friendly interface to help the risk analysis process in mines. Using the TRAM, the user can perform the risk analysis of hazards at the event level to group level and can progress to overall mine level. The snapshot of the TRAM is presented in Figure 5.9. The components of the TRAM are menu bar, list of hazard events panel, risk parameters input panel, risk level of hazard events panel, controls of hazard events, AHP input panel, risk level of hazard groups' panel, and overall risk level of mine panel.

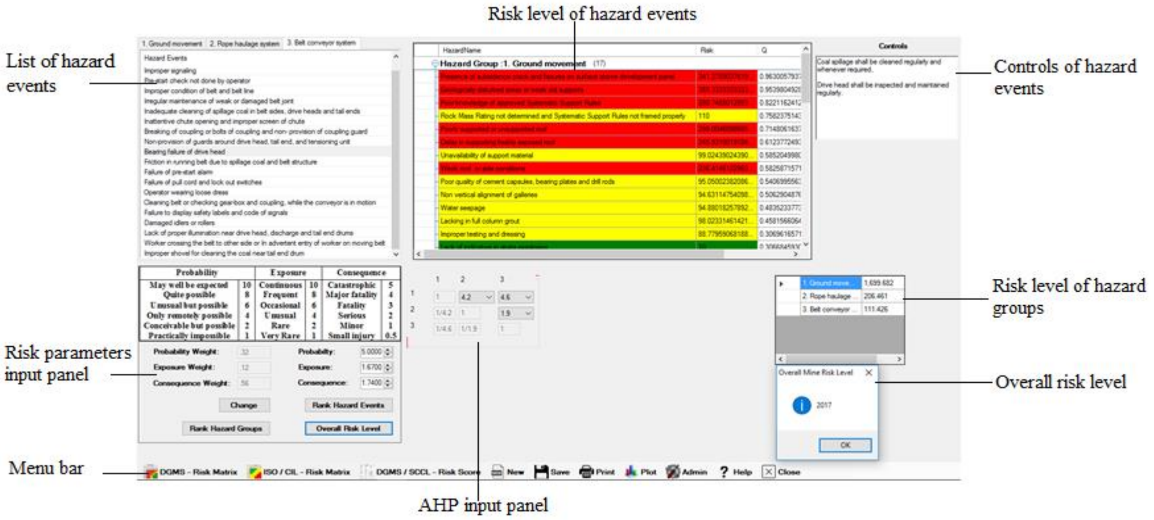


Figure 5.9 Snapshot of TRAM

Current risk assessment techniques followed in the Indian mining industry like DGMS-Risk Matrix, ISO/CIL-Risk Matrix, DGMS/SCCL Risk Score were also included as separate GUI forms in the Menu bar. The GUIs of DGMS-Risk Matrix, ISO/CIL-Risk Matrix, DGMS/SCCL Risk Score is represented in Figure 5.10.

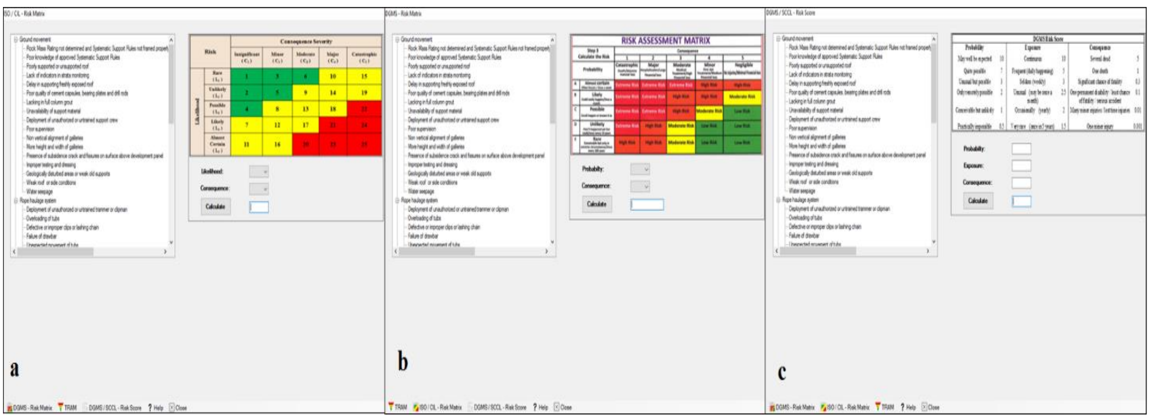


Figure 5.10 GUIs of a) ISO/CIL-Risk Matrix, b) DGMS-Risk Matrix, c) DGMS/SCCL Risk Score

The following are the contents of the menu bar:

a. **DGMS-Risk Matrix:** opens a new page with DGMS suggested risk matrix (DGMS, 2002)
b. **DGMS/SCCL Risk Score:** opens a new page with DGMS suggested risk score (DGMS, 2014a)
c. **ISO/CIL-Risk Matrix:** opens a new page with CIL suggested risk matrix (Sabir et al., 2012)
d. **New:** opens a new TRAM page
e. **Save:** saves the risk assessment process in .pdf format.
f. **Print:** prints the details, risk levels and rankings of hazard event and hazard group
g. **Plot:** plots the contents of hazard event and hazard group as a bar chart
h. **Admin:** the number of hazard groups and events can be added/removed/modified as shown in Figure 5.11.
i. **Help:** provides the user manual
j. **Close:** closes TRAM

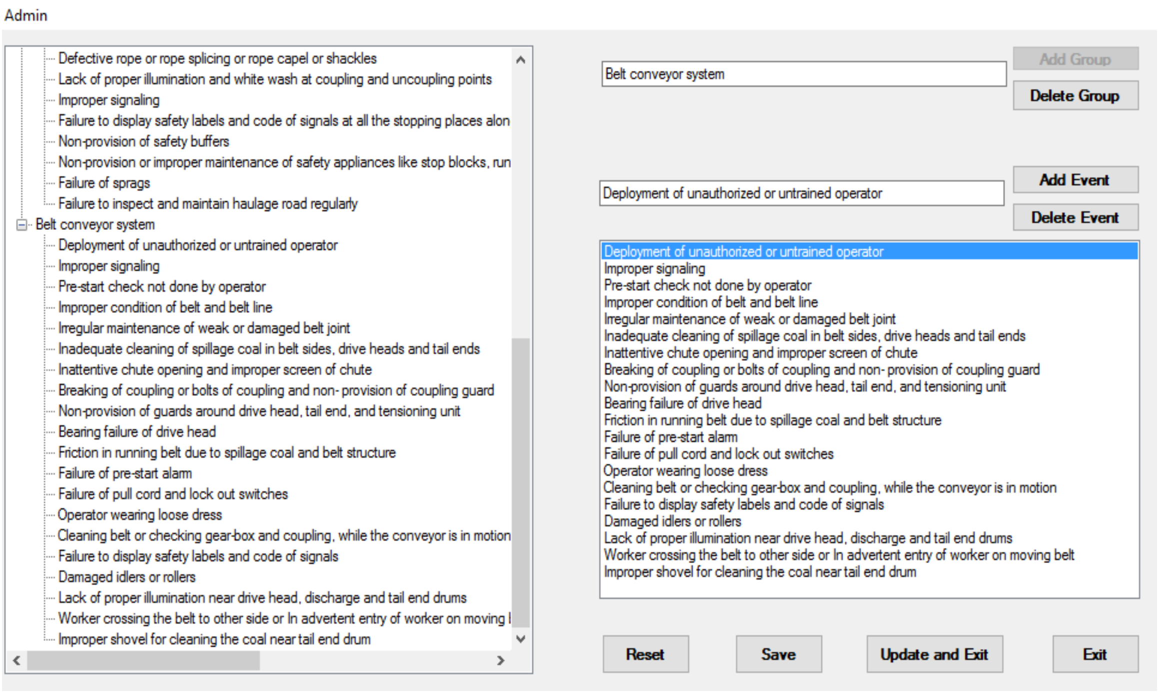


Figure 5.11 Admin tab

The active, latent, and indirect causes, which contributed to the mine accident or incident were recorded as hazard events. The list of hazard events was positioned at the top left corner of the user interface. The risk parameters input panel consisted of linguistic scales used by fuzzy logic in calculating the risk level of hazard events, text boxes for entering risk parameters weights and values, and buttons for calculating hazard events, groups, and overall risk level. The risk parameter weights can be modified using 'Change' button. The risk level of hazard events calculated based on the fuzzy logic and their rankings based on the VIKOR method will be displayed in risk level panel. The hazard events will be presented in the descending order of riskiness, i.e. the hazard event with the highest risk in the hazard group will be at the top of the group, and the hazard event with the lowest risk in the hazard group will be at the bottom of the group.

Based on the risk level of the hazard event, the suggested remedial measure of that event will be displayed in the Control box. The number of pairs in the AHP input panel is equal to the number the hazard groups, and they change dynamically with the change in hazard groups. The overall risk level of mine and risk level of hazard groups calculated considering AHP weights will be displayed in two different panels at the right bottom of the TRAM.

5.3. The Application of the Proposed Methodology

The proposed methodology was applied to six underground coal mines (mine-1, mine-2, mine-3, mine-4, mine-5, and mine-6) to evaluate the safety risk of the mines. The data was collected using the designed survey questionnaires and the collected data was evaluated using the TRAM.

5.3.1. Data collection

The six mines were visited some days during 2017 and 2018 for conducting questionnaire surveys. The questionnaires presented in Appendix A were used to collect the experts' opinion on the risk parameters of the hazard events and the relative importance of risk parameters in the hazard group. The questionnaire presented in Appendix B was used to collect the experts' opinion on the relative importance of hazard factors. Experts' through face-to-face interviews completed the questionnaires. The interviews were conducted during the beginning and the end of the shift hours when the experts could spare time for discussion. A total of 135 experts were interviewed from the six mines for collecting opinion on risk parameters of the hazard events and relative importance of the hazard factors present in their mines. The number of questionnaires considered in this study after excluding the partially filled questionnaires was presented in Table 5.4. The analysis of AHP questionnaires collected showed that 43 questionnaires have the consistency ratio less than 0.1. Therefore, 43 questionnaires data were considered for determining the relative importance of the hazard groups.

Table 5.4 Number of completely filled questionnaires collected

Questionnaires	Risk parameters data	Weights of hazard factors data
Ground movement	110	58
Transportation machinery (non-winding)	106	59
Machinery other than transportation machinery	105	58
Explosives	93	48
Electricity	104	58
Dust, gas and other combustible materials	102	60
Other causes	104	57

5.3.2. Analysis and Results

5.3.2.1. Risk estimation at the hazardous event level

Once the experts' opinion on the risk parameters of the hazard events and pairwise comparison of risk parameters was collected, the risk parameters data was converted to fuzzy values using the rating scales presented in Table 5.2. Then the fuzzy values were aggregated using equation 3.2, and the aggregated fuzzy values were defuzzified into crisp values using equation 3.3. The defuzzified experts' opinion on risk parameters and the relative importance of the risk parameters of the six mines were presented in Appendix D. The crisp values of P, E, and C of hazard events shown in Appendix D were the inputs used to estimate the risk level of the hazard events. Table 5.5 presents the risk level of the hazard events of the six mines calculated using the TRAM. The snapshots of the risk evaluation in mine-1 using TRAM were presented in Figures 5.12–5.18. The risk level at hazard group was calculated using equation 3.7 as shown in Table 5.6.

Table 5.5 The risk level of hazard events for six mines

Hazard group/ factors	Hazard event	Mine-1	Mine-2	Mine-3	Mine-4	Mine-5	Mine-6
Ground movement – Roof and side fall	GM1	105.11	108.76	110.00	107.99	106.55	101.14
	GM2	109.03	225.27	110.00	166.74	199.59	165.06
	GM3	324.34	180.80	110.00	288.93	221.75	230.97
	GM4	68.39	96.29	98.27	10.00	97.27	87.72
	GM5	204.14	246.47	264.35	110.00	255.40	106.75
	GM6	86.25	38.65	89.31	10.00	62.91	66.68

	GM7	101.46	88.17	98.40	10.00	92.62	91.65
	GM8	160.71	96.24	98.18	103.44	229.96	75.26
	GM9	94.08	96.72	97.22	99.02	97.96	94.91
	GM10	10.00	72.41	95.55	86.31	97.96	88.29
	GM11	96.24	102.52	98.40	88.02	96.85	90.38
	GM12	10.00	10.00	88.74	10.00	70.16	10.00
	GM13	334.54	321.42	258.02	364.29	303.34	272.42
	GM14	105.93	102.52	98.40	95.82	101.23	99.76
	GM15	361.32	383.33	301.15	340.44	353.70	285.72
	GM16	105.97	222.07	184.61	88.03	100.95	104.56
	GM17	10.00	10.00	92.62	10.00	10.00	43.47
Transport machinery (non-winding) - Rope haulage and conveyor	TM1	72.69	94.24	93.11	33.98	93.36	72.68
	TM2	10.00	10.00	93.82	10.00	92.58	85.70
	TM3	10.00	10.00	10.00	10.00	10.00	10.00
	TM4	91.99	51.09	91.11	48.69	94.59	93.61
	TM5	96.24	96.37	222.23	92.36	101.64	99.02
	TM6	95.99	88.79	96.65	33.66	97.11	77.92
	TM7	10.00	10.00	89.22	10.00	85.31	10.00
	TM8	149.12	103.51	97.61	93.73	97.96	96.21
	TM9	10.00	87.44	84.93	10.00	94.32	92.82
	TM10	10.00	10.00	83.17	10.00	81.87	74.57
	TM11	73.65	94.91	10.00	10.00	10.00	10.00
	TM12	97.81	81.56	96.42	89.01	96.78	96.85
	TM13	10.00	10.00	49.85	10.00	79.75	10.00
	TM14	255.93	270.09	280.27	189.62	110.00	107.59
	TM15	101.46	96.05	93.33	10.00	95.70	95.70
	TM16	99.35	103.36	92.99	10.00	97.96	102.41
	TM17	94.54	36.04	57.68	105.57	89.34	84.56
	TM18	10.00	10.00	91.07	46.81	90.39	62.48
	TM19	10.00	79.24	95.48	97.88	67.61	10.00
	TM20	103.05	170.17	83.51	94.91	67.61	87.65
	TM21	10.00	10.00	10.00	10.00	10.00	10.00
	TM22	93.81	103.90	88.24	71.26	90.45	90.90
	TM23	10.00	10.00	10.00	10.00	10.00	72.75
	TM24	10.00	10.00	10.00	10.00	10.00	10.00
	TM25	64.63	84.37	85.73	10.00	10.00	10.00
	TM26	10.00	85.56	10.00	10.00	10.00	10.00
	TM27	215.80	102.04	96.19	106.64	99.88	105.74
	TM28	10.00	88.46	10.00	10.00	10.00	10.00
	TM29	97.21	99.84	56.09	10.00	10.00	10.00
	TM30	99.93	223.30	89.00	99.02	77.92	90.67
	TM31	93.96	94.24	90.05	95.31	85.96	84.87
	TM32	78.59	95.59	10.00	54.04	10.00	10.00
	TM33	10.00	10.00	10.00	10.00	10.00	10.00

	TM34	93.71	88.08	63.85	10.00	10.00	88.75
	TM35	85.56	10.00	10.00	97.42	90.33	78.38
	TM36	10.00	10.00	10.00	10.00	10.00	10.00
Machinery other than transport machinery – LHD/SDL, Haulage engine	MM1	78.36	99.84	88.19	10.00	98.07	63.70
	MM2	88.29	10.00	97.71	10.00	96.93	93.56
	MM3	91.46	96.05	10.00	10.00	77.13	10.00
	MM4	10.00	10.00	10.00	10.00	84.80	10.00
	MM5	98.48	88.46	103.27	92.85	84.92	93.66
	MM6	106.74	110.00	96.88	106.64	104.25	105.88
	MM7	70.56	10.00	59.07	10.00	87.91	79.85
	MM8	98.09	75.86	87.62	92.61	87.62	98.48
	MM9	98.01	94.24	199.92	93.51	98.07	101.59
	MM10	73.72	10.00	83.10	10.00	92.48	63.16
	MM11	68.92	89.54	10.00	10.00	76.26	10.00
	MM12	10.00	10.00	10.00	10.00	59.69	10.00
	MM13	108.20	107.12	96.46	93.26	96.16	92.56
	MM14	62.98	10.00	10.00	10.00	75.76	10.00
	MM15	10.00	10.00	98.73	10.00	86.52	90.26
	MM16	10.00	62.39	10.00	10.00	10.00	79.29
	MM17	10.00	10.00	74.44	10.00	60.16	26.61
	MM18	10.00	10.00	10.00	10.00	10.00	10.00
	MM19	127.55	214.74	86.80	104.83	100.54	157.49
	MM20	93.66	94.99	90.79	10.00	91.11	99.93
	MM21	93.77	104.77	95.37	93.73	101.90	101.59
	MM22	99.33	101.34	96.60	73.69	95.94	97.30
	MM23	96.17	106.20	107.52	201.35	101.23	196.51
	MM24	104.51	104.98	103.65	269.15	104.78	101.50
	MM25	98.67	99.84	116.60	97.69	97.71	173.07
	MM26	274.77	132.75	151.66	296.71	210.44	141.72
	MM27	106.66	99.84	106.47	96.93	106.28	98.54
	MM28	95.56	92.72	92.99	87.62	10.00	89.22
	MM29	96.37	85.31	102.38	10.00	75.90	96.33
	MM30	10.00	79.67	95.33	10.00	77.98	94.58
Explosives - Shot firing and blasting	SF1	100.70	99.02	101.90	95.38	99.02	106.71
	SF2	10.00	10.00	10.00	10.00	83.21	86.21
	SF3	95.67	99.02	104.85	92.05	103.51	100.70
	SF4	101.52	87.48	87.76	94.91	101.14	100.70
	SF5	102.19	97.89	103.40	103.23	97.61	101.60
	SF6	97.96	99.02	10.00	97.33	89.62	85.32
	SF7	78.46	94.11	95.28	97.33	104.56	97.02
	SF8	10.00	10.00	81.99	10.00	83.30	10.00
	SF9	10.00	10.00	65.38	10.00	67.51	78.08
	SF10	10.00	10.00	10.00	92.44	10.00	10.00

	SF11	95.44	97.81	97.17	97.69	101.14	100.95
	SF12	97.96	94.69	107.54	108.39	107.03	106.90
	SF13	98.34	92.22	92.04	105.05	89.69	99.02
	SF14	105.74	96.24	94.91	106.81	96.14	99.31
Electricity	EL1	10.00	65.98	10.00	99.02	10.00	10.00
	EL2	10.00	64.06	10.00	97.69	93.01	10.00
	EL3	93.95	98.02	97.96	107.59	88.46	95.47
	EL4	10.00	88.30	10.00	88.88	10.00	10.00
	EL5	87.98	96.72	61.88	99.02	61.96	86.69
	EL6	88.45	96.24	97.96	10.00	77.08	10.00
	EL7	10.00	10.00	10.00	10.00	10.00	10.00
	EL8	82.04	10.00	99.02	10.00	76.28	10.00
	EL9	10.00	10.00	85.83	10.00	10.00	75.76
	EL10	10.00	10.00	10.00	10.00	10.00	10.00
	EL11	10.00	81.07	10.00	10.00	60.88	10.00
	EL12	10.00	10.00	10.00	75.76	10.00	10.00
	EL13	10.00	147.82	10.00	97.33	92.96	88.35
	EL14	10.00	78.11	10.00	50.46	82.40	10.00
	EL15	10.00	10.00	26.06	10.00	10.00	92.79
	EL16	10.00	10.00	66.81	10.00	10.00	68.01
	EL17	10.00	81.40	90.56	96.18	92.33	90.27
	EL18	10.00	10.00	67.08	10.00	77.67	10.00
Dust, gas and other combustible materials – Explosion, ventilation, mine fire	EX1	165.64	162.16	255.86	110.00	247.19	132.87
	EX2	107.55	110.00	183.96	100.84	256.56	202.56
	EX3	110.00	128.98	99.02	110.00	108.08	94.22
	EX4	197.09	197.41	233.70	208.59	222.88	218.02
	EX5	267.47	176.27	259.62	283.93	218.45	263.27
	EX6	110.00	110.00	232.52	106.42	221.25	233.67
	EX7	102.68	95.34	235.28	87.41	216.22	183.57
	EX8	156.84	153.17	103.30	88.02	217.49	145.50
	EX9	274.31	285.99	264.35	234.77	271.41	230.89
	EX10	354.09	287.68	344.05	203.98	371.81	315.75
	EX11	139.74	182.93	110.00	108.28	217.72	103.97
	EX12	169.96	110.00	238.87	110.00	244.49	238.07
	EX13	110.00	105.78	104.51	110.00	108.02	105.29
	EX14	97.43	106.94	198.76	95.90	289.73	153.64
	EX15	284.91	278.52	254.61	308.61	193.01	223.49
	EX16	302.04	132.89	233.31	167.11	262.73	101.82
	EX17	98.54	101.90	104.25	110.00	95.90	100.37
	EX18	110.00	110.00	107.81	110.00	104.22	98.03
	EX19	110.00	108.45	110.00	110.00	104.22	108.66
	EX20	107.87	105.48	201.85	110.00	100.41	152.31
	EX21	59.38	49.65	82.45	101.66	163.96	81.57
	EX22	95.01	10.00	211.51	86.01	210.55	66.68

	EX23	116.13	100.05	236.86	213.11	212.74	207.95
	EX24	99.84	102.50	108.88	98.16	99.02	94.11
	EX25	96.29	100.26	99.02	92.13	97.83	103.38
	EX26	184.67	94.91	224.72	172.74	168.28	99.02
	EX27	101.34	94.91	99.02	110.00	94.98	105.79
	EX28	105.16	106.28	110.00	110.00	105.75	103.97
	EX29	101.34	94.91	98.07	100.41	101.06	94.11
	EX30	98.54	98.40	105.35	87.37	102.79	103.17
	EX31	103.90	107.34	107.97	106.57	97.41	102.17
	EX32	105.96	110.00	139.69	110.00	128.08	110.00
	EX33	105.03	103.98	110.00	176.00	110.00	203.12
	EX34	110.00	110.00	110.00	233.22	108.33	107.68
	EX35	10.00	10.00	92.48	10.00	74.48	87.27
	EX36	219.91	108.63	110.00	232.43	178.14	108.83
	EX37	266.68	228.71	268.98	196.42	237.51	230.26
	EX38	275.41	248.05	306.06	301.40	265.39	299.68
	EX39	296.93	301.15	269.22	351.30	332.50	254.05
	EX40	99.84	92.04	100.54	104.83	106.64	105.05
	EX41	271.55	311.20	214.40	273.75	246.55	235.15
	EX42	301.62	228.74	216.11	98.16	235.92	188.84
	EX43	254.07	259.62	270.26	110.00	220.42	239.31
	EX44	257.34	319.53	108.13	290.14	197.24	238.53
Other causes – Inundation, Unclassified	OC1	90.87	208.68	174.61	110.00	97.43	231.74
	OC2	10.00	80.57	86.54	10.00	10.00	10.00
	OC3	216.57	276.13	277.99	257.22	262.93	292.95
	OC4	99.76	108.67	221.26	207.88	135.82	103.27
	OC5	97.77	97.89	97.96	99.02	98.54	98.59
	OC6	94.11	10.00	95.44	10.00	92.67	10.00
	OC7	107.41	102.01	105.83	104.25	103.90	101.56
	OC8	75.91	10.00	96.65	35.48	84.50	10.00
	OC9	97.61	100.89	102.56	103.11	92.32	94.91
	OC10	170.86	181.57	186.76	107.84	135.85	200.57
	OC11	109.04	107.73	106.05	96.93	101.34	104.87
	OC12	105.53	102.52	104.73	101.90	96.05	102.22
	OC13	269.25	325.40	271.23	218.06	278.99	227.53
	OC14	98.59	165.75	192.41	99.02	92.24	110.00
	OC15	97.30	91.13	85.89	94.03	86.68	10.00
	OC16	103.92	104.40	100.51	99.02	106.79	107.11
	OC17	97.61	102.77	92.62	76.47	94.55	95.70
	OC18	257.12	236.15	107.81	103.51	96.11	104.62

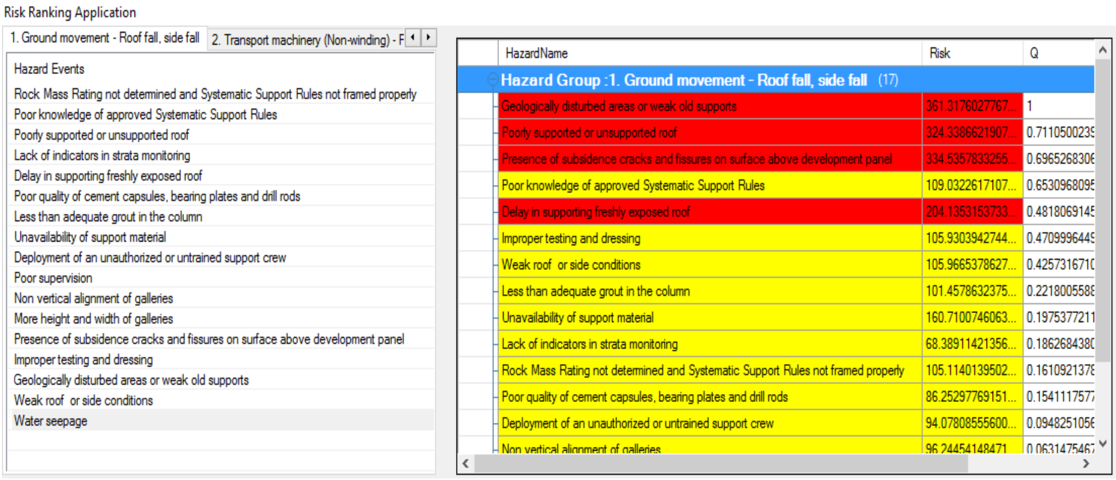


Figure 5.12 Risk evaluation of ground movement

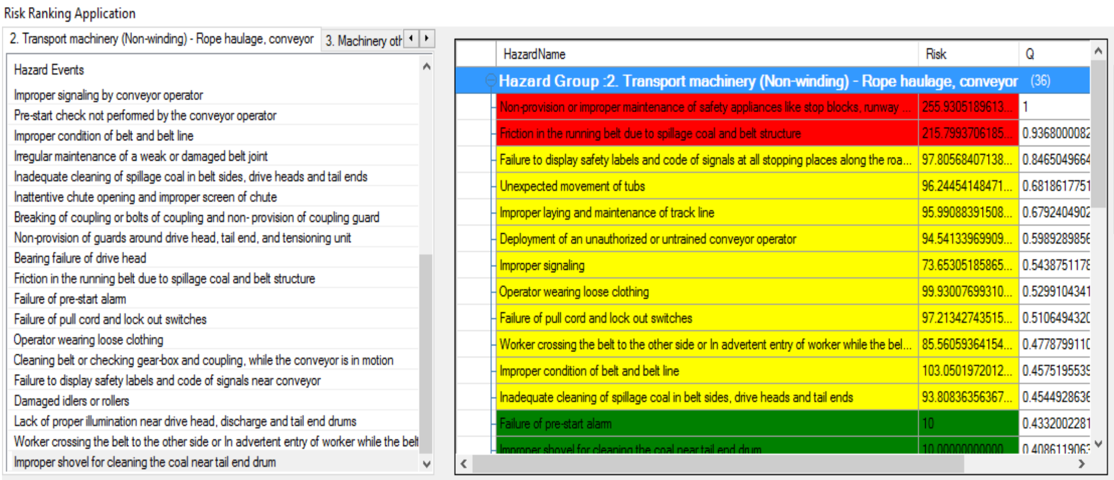


Figure 5.13 Risk evaluation of transport machinery

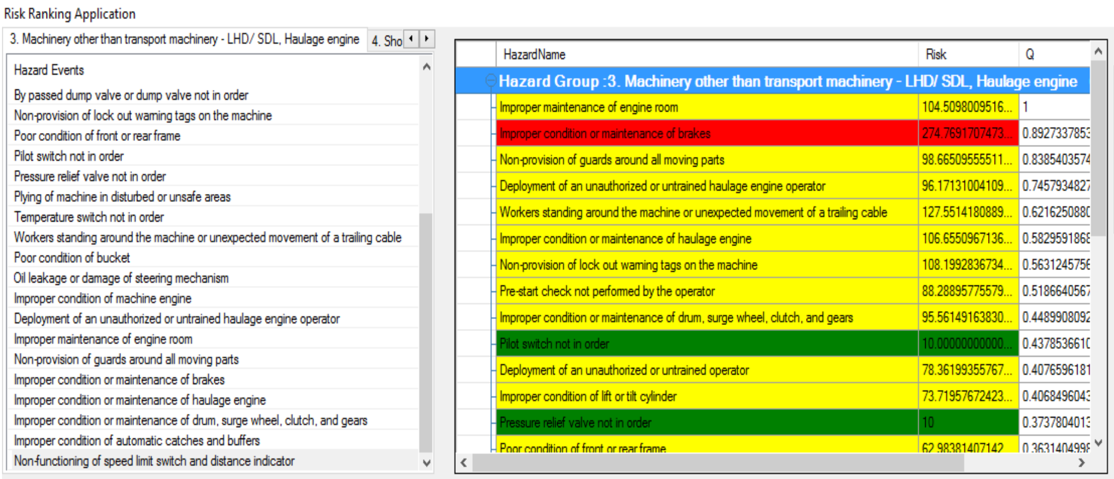


Figure 5.14 Risk evaluation of machinery other than transport machinery

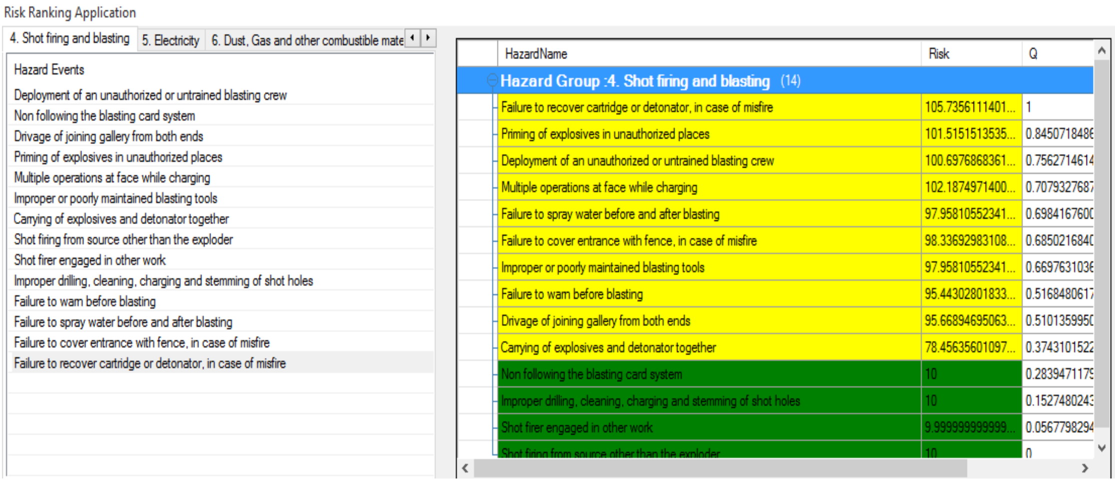


Figure 5.15 Risk evaluation of explosives - shot firing and blasting

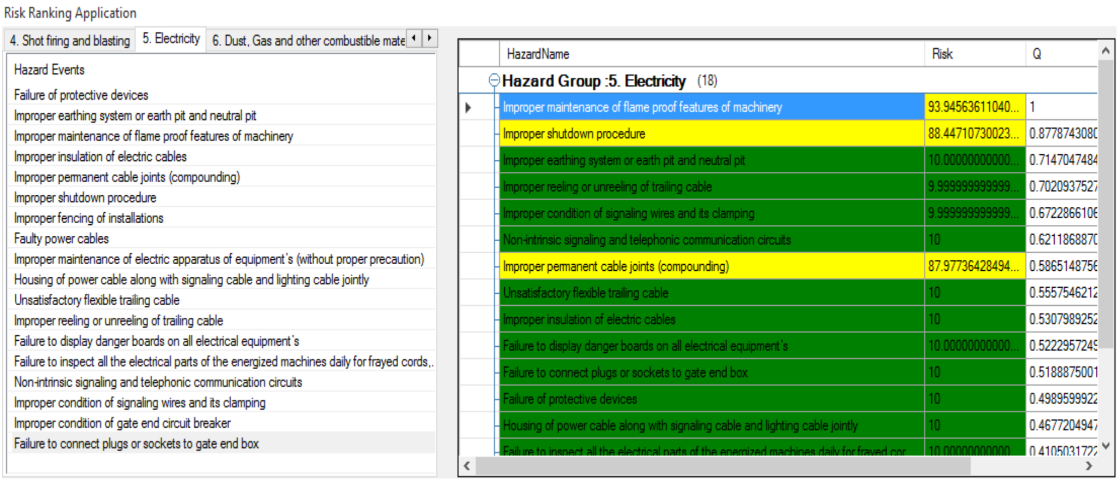


Figure 5.16 Risk evaluation of electricity

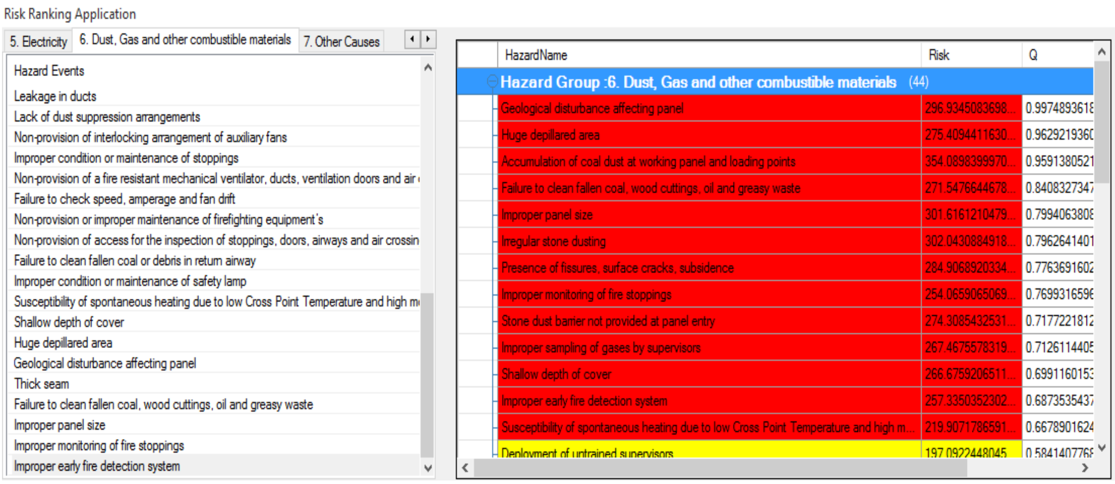


Figure 5.17 Risk evaluation of dust, gas and other combustible materials

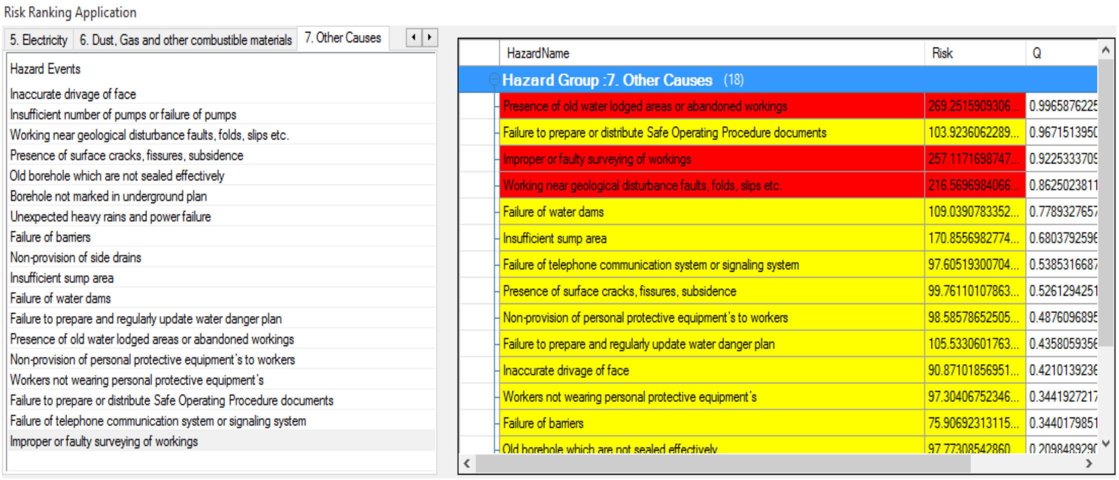


Figure 5.18 Risk evaluation of other causes - inundation

Table 5.6 The risk level of hazard groups (RL_{HG}) at hazardous group levels

Hazard group	Mine-1 RL_{HG1}	Mine-2 RL_{HG2}	Mine-3 RL_{HG3}	Mine-4 RL_{HG4}	Mine-5 RL_{HG5}	Mine-6 RL_{HG6}
Ground movement	2287.51	2401.64	2293.22	1989.03	2498.20	2014.74
Transport machinery (non-winding)	2405.02	2638.24	2571.60	1639.91	2208.42	2081.83
Machinery other than transport machinery	2400.83	2230.65	2401.55	1960.57	2560.54	2496.38
Explosives	1013.98	997.50	1062.22	1120.61	1233.48	1182.52
Electricity	492.42	977.72	783.16	901.93	883.03	707.34
Dust, gas and other combustible materials	7112.10	6440.75	7675.35	6639.67	7967.36	6975.66
Other causes	2199.23	2412.26	2506.85	1933.74	2066.71	2015.64

5.3.2.2. Risk prioritization at the hazardous event level

Concurrently, the average of the pairwise comparison of risk parameters data was calculated, and weights were determined using the AHP method. The crisp values of P, E, and C of hazard events shown in Appendix D were the inputs used to prioritize the hazard events. Table 5.7 presents the prioritization of the hazard events of the six mines calculated using the TRAM. In this study, the prioritization presented was based on the ideal solution (Q index) values of VIKOR technique.

Table 5.7 Ranking of hazard events for six mines

Hazard group/ factors	Hazard event	Mine-1	Rank	Mine-2	Rank	Mine-3	Rank	Mine-4	Rank	Mine-5	Rank	Mine-6	Rank

Ground movement – Roof and side fall														
GM15	GM14	GM13	GM12	GM11	GM10	GM9	GM8	GM7	GM6	GM5	GM4	GM3	GM2	GM1
1.000	0.471	0.697	0.046	0.063	0.039	0.095	0.198	0.222	0.154	0.482	0.187	0.711	0.653	0.162
1	6	3	15	14	16	13	9	8	12	5	10	2	4	11
1.000	0.368	0.839	0.075	0.100	0.008	0.034	0.141	0.017	0.146	0.894	0.235	0.764	0.760	0.230
1	7	3	14	12	17	15	11	16	10	2	8	4	5	9
1.000	0.448	0.712	0.199	0.047	0.138	0.071	0.256	0.147	0.000	0.752	0.275	0.935	0.832	0.177
1	6	5	10	16	14	15	9	13	17	4	8	2	3	11
0.991	0.418	0.894	0.009	0.087	0.106	0.195	0.231	0.091	0.031	0.895	0.048	0.942	0.963	0.269
1	6	5	16	13	11	10	9	12	15	4	14	3	2	8
1.000	0.486	0.750	0.190	0.130	0.213	0.275	0.386	0.238	0.182	0.807	0.309	0.866	0.684	0.282
1	6	4	14	16	13	11	8	12	15	3	9	2	5	10
1.000	0.474	0.629	0.000	0.181	0.111	0.173	0.121	0.220	0.051	0.535	0.179	0.674	0.560	0.319
1	7	3	17	10	14	12	13	9	16	5	11	2	4	8

Transport machinery (non-winding) - Rope haulage and conveyor														
TM13	TM12	TM11	TM10	TM9	TM8	TM7	TM6	TM5	TM4	TM3	TM2	TM1	GM17	GM16
0.143	0.847	0.544	0.066	0.095	0.395	0.180	0.679	0.682	0.212	0.153	0.102	0.182	0.000	0.426
32	3	7	35	34	15	27	5	4	24	31	33	26	17	7
0.350	0.199	0.186	0.184	0.280	0.664	0.238	0.212	0.203	0.000	0.221	0.020	0.302	0.092	0.490
12	24	27	28	17	3	18	21	23	36	20	35	16	13	6
0.248	0.705	0.488	0.290	0.293	0.450	0.272	0.767	0.779	0.367	0.089	0.395	0.301	0.153	0.361
29	4	10	27	26	13	28	3	2	20	34	17	24	12	7
0.194	0.528	0.488	0.042	0.094	0.302	0.114	0.360	0.593	0.235	0.104	0.092	0.247	0.005	0.341
25	5	8	35	31	17	29	14	3	21	30	32	20	17	7
0.239	0.689	0.380	0.210	0.334	0.399	0.221	0.688	0.815	0.280	0.197	0.248	0.308	0.000	0.434
26	4	14	29	17	12	28	5	2	21	30	25	18	17	7
0.070	0.772	0.469	0.242	0.309	0.355	0.145	0.535	0.821	0.360	0.046	0.242	0.154	0.062	0.494
32	4	6	23	18	15	30	5	3	14	34	25	29	15	6

TM28	TM27	TM26	TM25	TM24	TM23	TM22	TM21	TM20	TM19	TM18	TM17	TM16	TM15	TM14
0.433	0.937	0.166	0.332	0.223	0.329	0.454	0.174	0.458	0.159	0.368	0.599	0.390	0.297	1.000
13	2	29	19	23	20	12	28	11	30	18	6	16	21	1
0.330	0.652	0.085	0.193	0.234	0.131	0.308	0.099	0.516	0.208	0.197	0.321	1.000	0.551	0.711
13	4	32	26	19	30	15	31	7	22	25	14	1	6	2
0.534	0.667	0.141	0.517	0.192	0.233	0.457	0.000	0.298	0.406	0.354	0.520	0.385	0.366	1.000
7	5	33	9	31	30	12	36	25	16	22	8	18	21	1
0.299	0.895	0.013	0.059	0.207	0.467	0.505	0.053	0.370	0.373	0.188	0.588	0.345	0.133	1.000
18	2	36	33	23	9	7	34	13	12	26	4	15	28	1
0.296	0.717	0.031	0.270	0.127	0.287	0.431	0.069	0.250	0.250	0.249	0.537	0.371	0.373	1.000
19	3	34	22	31	20	8	33	23	23	24	6	16	15	1
0.300	0.945	0.031	0.341	0.255	0.297	0.398	0.009	0.266	0.199	0.193	0.442	0.452	0.339	1.000
19	2	35	16	22	20	13	36	21	26	27	9	8	17	1

Machinery other than transport machinery – LHD/SDL, Haulage engine														
MM7	MM6	MM5	MM4	MM3	MM2	MM1	TM36	TM35	TM34	TM33	TM32	TM31	TM30	TM29
0.085	0.127	0.108	0.061	0.212	0.519	0.408	0.408	0.478	0.250	0.000	0.187	0.382	0.530	0.511
26	23	24	27	21	8	11	14	10	22	36	25	17	8	9
0.242	0.353	0.269	0.165	0.237	0.516	0.536	0.065	0.068	0.510	0.156	0.361	0.407	0.605	0.353
22	17	19	26	23	11	10	34	33	8	29	10	9	5	11
0.064	0.158	0.225	0.071	0.110	0.364	0.224	0.472	0.410	0.422	0.021	0.144	0.368	0.327	0.636
25	22	18	24	23	12	19	11	15	14	35	32	19	23	6
0.033	0.930	0.565	0.287	0.311	0.105	0.470	0.195	0.392	0.268	0.186	0.219	0.430	0.528	0.320
28	1	8	23	19	27	11	24	11	19	27	22	10	7	16
0.128	0.798	0.467	0.263	0.372	0.208	0.240	0.387	0.409	0.233	0.026	0.081	0.400	0.401	0.453
27	4	10	19	14	22	21	13	9	27	35	32	11	10	7
0.283	0.254	0.070	0.124	0.034	0.410	0.355	0.466	0.413	0.169	0.048	0.098	0.242	0.402	0.430
18	21	26	24	27	10	14	7	11	28	33	31	24	12	10

	MM8	0.270	17	0.617	6	0.264	16	0.483	10	0.549	7	0.246	22
	MM9	0.256	18	0.616	7	0.614	5	0.598	7	0.675	5	0.377	12
	MM10	0.407	12	0.491	13	0.488	9	0.111	26	0.159	25	0.532	6
	MM11	0.232	19	0.274	18	0.013	28	0.328	18	0.160	24	0.022	29
	MM12	0.052	28	0.063	28	0.006	30	0.248	24	0.019	29	0.032	28
	MM13	0.563	7	0.802	3	0.532	6	0.436	14	0.168	23	0.440	9
	MM14	0.363	14	0.468	14	0.185	21	0.027	29	0.065	28	0.265	19
	MM15	0.438	10	0.786	4	0.515	7	0.000	30	0.158	26	0.461	7
	MM16	0.374	13	0.248	20	0.270	15	0.299	21	0.242	20	0.328	15
	MM17	0.000	30	0.039	29	0.246	17	0.310	20	0.387	13	0.137	23
	MM18	0.087	25	0.073	27	0.008	29	0.118	25	0.004	30	0.303	17
	MM19	0.622	5	1.000	1	0.442	11	0.619	6	0.617	6	0.682	4
	MM20	0.181	22	0.384	15	0.277	14	0.290	22	0.459	11	0.379	11
	MM21	0.044	29	0.172	25	0.051	26	0.877	3	0.832	3	0.117	25
	MM22	0.280	16	0.551	9	0.218	20	0.442	13	0.508	8	0.308	16

Explosives - Shot firing and blasting														
SF7	SF6	SF5	SF4	SF3	SF2	SF1	MM30	MM29	MM28	MM27	MM26	MM25	MM24	MM23
0.374	0.670	0.708	0.845	0.510	0.284	0.756	0.228	0.332	0.449	0.583	0.893	0.839	1.000	0.746
10	7	4	2	9	11	3	20	15	9	6	2	3	1	4
0.587	0.803	0.719	0.549	1.000	0.274	0.885	0.244	0.020	0.370	0.220	0.497	0.591	0.825	0.694
7	4	5	9	1	11	3	21	30	16	24	12	8	2	5
0.525	0.286	0.773	0.468	0.838	0.239	0.741	0.029	0.312	0.470	0.490	0.807	0.866	0.831	1.000
6	11	3	9	2	12	4	27	13	10	8	4	2	3	1
0.616	0.445	0.826	0.647	0.491	0.270	0.845	0.421	0.468	0.539	0.664	0.894	0.341	0.420	0.677
8	11	5	6	10	12	4	15	12	9	5	2	17	16	4
0.791	0.279	0.519	0.762	0.846	0.407	0.797	0.351	0.426	0.332	0.889	1.000	0.343	0.363	0.500
5	12	8	6	2	9	4	16	12	18	2	1	17	15	9
0.583	0.328	0.720	0.768	0.699	0.326	0.966	0.000	0.260	0.360	0.444	0.669	0.912	1.000	0.905
9	10	4	3	5	11	2	30	20	13	8	5	2	1	3

Electricity														
EL8	EL7	EL6	EL5	EL4	EL3	EL2	EL1	SF14	SF13	SF12	SF11	SF10	SF9	SF8
0.330	0.000	0.878	0.587	0.531	1.000	0.715	0.499	1.000	0.685	0.698	0.517	0.153	0.057	0.000
15	18	2	7	9	1	3	12	1	6	5	8	12	13	14
0.266	0.141	0.799	0.671	0.526	0.541	0.274	0.380	0.887	0.510	0.550	0.640	0.224	0.029	0.011
13	16	2	3	5	4	12	9	2	10	8	6	12	13	14
0.435	0.000	1.000	0.455	0.267	0.947	0.560	0.283	0.571	0.504	1.000	0.500	0.347	0.006	0.011
9	18	1	7	13	2	5	12	5	7	1	8	10	14	13
0.204	0.133	0.369	0.545	0.313	1.000	0.559	0.652	0.948	0.868	1.000	0.617	0.555	0.087	0.000
15	16	11	4	13	1	3	2	2	3	1	7	9	13	14
0.132	0.069	0.506	0.492	0.231	1.000	0.711	0.482	0.557	0.373	1.000	0.798	0.234	0.288	0.000
16	17	6	7	14	1	3	8	7	10	1	3	13	11	14
0.194	0.019	0.343	0.353	0.331	1.000	0.358	0.517	0.685	0.648	1.000	0.688	0.051	0.175	0.000
12	17	10	9	11	1	8	6	7	8	1	6	13	12	14

Dust, gas and other combustible materials														
EX5	EX4	EX3	EX2	EX1	EL18	EL17	EL16	EL15	EL14	EL13	EL12	EL11	EL10	EL9
0.713	0.584	0.520	0.350	0.549	0.519	0.240	0.672	0.621	0.411	0.522	0.702	0.556	0.467	0.072
10	14	17	27	16	11	16	5	6	14	10	4	8	13	17
0.634	0.674	0.696	0.775	0.690	0.248	0.387	0.047	0.135	0.404	1.000	0.379	0.451	0.146	0.321
19	17	14	9	15	14	8	18	17	7	1	10	6	15	11
0.771	0.502	0.194	0.443	0.587	0.615	0.109	0.607	0.339	0.253	0.440	0.509	0.298	0.223	0.226
4	17	35	24	13	3	17	4	10	14	8	6	11	16	15
0.756	0.531	0.863	0.447	0.723	0.463	0.401	0.106	0.391	0.221	0.372	0.455	0.371	0.334	0.000
15	30	7	33	18	5	7	17	8	14	9	6	10	12	18
0.269	0.280	0.574	0.968	0.958	0.338	0.217	0.292	0.576	0.389	0.442	0.780	0.529	0.301	0.000
36	35	17	2	4	11	15	13	4	10	9	2	5	12	18
0.773	0.557	0.380	0.758	0.815	0.514	0.145	0.662	0.813	0.153	0.801	0.663	0.150	0.000	0.154
12	32	38	17	8	7	16	5	2	14	3	4	15	18	13

EX20	EX19	EX18	EX17	EX16	EX15	EX14	EX13	EX12	EX11	EX10	EX9	EX8	EX7	EX6
0.311	0.285	0.225	0.032	0.796	0.776	0.432	0.285	0.564	0.502	0.959	0.718	0.518	0.300	0.427
29	32	34	43	6	7	22	33	15	19	3	9	18	31	23
0.614	0.741	0.790	0.485	0.689	0.905	0.495	0.567	0.748	0.670	0.594	0.611	0.452	0.343	0.702
21	11	8	32	16	4	30	26	10	18	23	22	32	37	13
0.467	0.259	0.140	0.069	0.530	0.598	0.476	0.317	0.594	0.302	1.000	0.698	0.616	0.536	0.662
23	33	37	41	16	11	21	27	12	29	1	5	10	15	7
0.705	0.796	0.938	0.846	0.565	0.887	0.204	0.726	0.904	0.662	0.446	0.633	0.080	0.265	0.682
20	10	1	8	27	5	42	17	3	22	34	24	43	39	21
0.281	0.411	0.411	0.190	0.411	0.697	0.515	0.594	0.960	0.778	0.780	0.758	0.238	0.411	0.379
34	25	24	41	26	10	19	15	3	6	5	7	38	27	30
0.636	0.729	0.431	0.516	0.569	0.814	0.433	0.641	0.978	0.571	0.769	0.889	0.634	0.939	0.692
27	19	37	34	31	9	36	26	2	30	14	4	28	3	21

	EX21	0.366	26	0.033	43	0.295	30	0.315	38	0.369	31	0.000	44
	EX22	0.203	35	0.158	41	0.483	20	0.208	41	0.199	40	0.186	43
	EX23	0.492	20	0.480	33	0.543	14	0.754	16	0.559	18	0.775	11
	EX24	0.000	44	0.493	31	0.081	39	0.520	31	0.318	33	0.325	40
	EX25	0.164	38	0.454	34	0.077	40	0.244	40	0.099	43	0.646	25
	EX26	0.473	21	0.149	42	0.484	19	0.318	37	0.261	37	0.228	42
	EX27	0.109	39	0.328	39	0.000	44	0.721	19	0.146	42	0.650	24
	EX28	0.175	37	0.531	28	0.275	31	0.811	9	0.477	22	0.620	29
	EX29	0.107	40	0.333	38	0.106	38	0.417	36	0.322	32	0.377	39
	EX30	0.077	42	0.574	24	0.056	43	0.561	28	0.497	21	0.760	16
	EX31	0.081	41	0.570	25	0.142	36	0.560	29	0.200	39	0.540	33
	EX32	0.316	28	0.906	3	0.380	26	0.771	14	0.697	9	0.837	7
	EX33	0.407	24	0.527	29	0.268	32	0.639	23	0.674	12	0.795	10
	EX34	0.386	25	0.851	7	0.258	34	0.891	4	0.680	11	0.730	18
	EX35	0.182	36	0.000	44	0.066	42	0.000	44	0.000	44	0.245	41

Other causes – Inundation, Unclassified														
OC6	OC5	OC4	OC3	OC2	OC1	EX44	EX43	EX42	EX41	EX40	EX39	EX38	EX37	EX36
0.205	0.210	0.526	0.863	0.029	0.421	0.687	0.770	0.799	0.841	0.304	0.997	0.963	0.699	0.668
15	14	8	4	17	11	12	8	5	4	30	1	2	11	13
0.342	0.119	0.479	0.900	0.000	0.634	0.862	0.964	0.625	0.733	0.274	0.867	0.546	0.431	0.910
13	14	9	3	18	6	6	1	20	12	40	5	27	36	2
0.027	0.001	0.729	1.000	0.085	0.639	0.425	0.646	0.494	0.683	0.313	0.898	0.849	0.651	0.469
15	18	6	1	14	9	25	9	18	6	28	2	3	8	22
0.000	0.259	0.812	1.000	0.037	0.571	0.794	0.779	0.438	0.776	0.504	0.919	0.613	0.612	0.875
18	13	4	1	17	6	11	12	35	13	32	2	25	26	6
0.223	0.499	0.632	0.606	0.064	0.498	0.668	0.603	0.384	0.502	0.586	0.981	0.426	0.383	0.729
16	7	3	4	17	8	13	14	28	20	16	1	23	29	8
0.272	0.208	0.577	1.000	0.000	0.726	0.714	0.677	0.879	0.689	0.772	1.000	0.766	0.474	0.844
12	14	8	1	18	5	20	23	5	22	13	1	15	35	6

OC18	OC17	OC16	OC15	OC14	OC13	OC12	OC11	OC10	OC9	OC8	OC7
0.922	0.538	0.967	0.344	0.487	0.997	0.435	0.779	0.680	0.000	0.344	0.061
3	7	2	13	9	1	10	5	6	18	13	16
0.941	0.425	0.838	0.096	0.554	1.000	0.396	0.644	0.577	0.077	0.354	0.113
2	10	4	16	8	1	11	5	7	17	12	15
0.840	0.545	0.894	0.011	0.667	0.975	0.389	0.848	0.653	0.140	0.307	0.020
5	10	3	17	7	2	11	4	8	13	12	16
0.878	0.176	0.576	0.227	0.560	0.922	0.337	0.568	0.492	0.278	0.120	0.290
3	15	5	14	8	2	10	7	9	12	16	11
0.519	0.435	0.354	0.000	0.437	1.000	0.460	0.832	0.468	0.396	0.413	0.565
6	12	15	18	11	1	10	2	9	14	13	5
0.758	0.518	0.975	0.134	0.574	0.749	0.257	0.691	0.683	0.089	0.366	0.140
3	10	2	16	9	4	13	6	7	17	11	15

5.3.2.3. Risk evaluation at the hazardous group level and mine level

Once the experts' opinion on the relative importance of the hazard groups was collected, the pairwise comparison of hazard groups data collected was averaged. The average of pairwise data collected from the six mines was presented in Appendix E. The pairwise comparison data shown in Appendix E were the inputs used to evaluate the relative importance of the hazard groups. Table 5.8 presents the weights of hazard groups of six mines calculated using the AHP method in TRAM. The consistency of the data was verified by calculating the consistency ratio as shown in Table 5.9.

Table 5.8 The weights of hazard factors at the hazardous group level

Hazard group	Mine-1	Mine-2	Mine-3	Mine-4	Mine-5	Mine-6
	W_1	W_2	W_3	W_4	W_5	W_6
Ground movement	0.35	0.30	0.37	0.30	0.40	0.32
Transport machinery (non-winding)	0.17	0.24	0.21	0.24	0.18	0.21
Machinery other than transport machinery	0.11	0.12	0.15	0.15	0.10	0.14
Explosives	0.12	0.12	0.12	0.09	0.07	0.11
Electricity	0.05	0.09	0.06	0.05	0.06	0.04
Dust, gas and other combustible materials	0.14	0.09	0.06	0.11	0.13	0.11
Other causes	0.06	0.05	0.04	0.06	0.06	0.06

Table 5.9 The consistency ratios of the risk parameters data

	Mine-1	Mine-2	Mine-3	Mine-4	Mine-5	Mine-6
λ_{max}	7.48	7.44	7.45	7.38	7.25	7.39
C.I	0.08	0.07	0.07	0.06	0.04	0.06
C.R	0.06	0.05	0.05	0.04	0.03	0.04

The risk levels of hazards factors at group level calculated as shown in Table 5.6 does not consider the weight contribution of hazard factors. Therefore, weights of hazard groups were calculated using AHP method and combined with the obtained risk levels of hazard groups of Table 5.6 to obtain the improved risk levels at the group level as presented in Table 5.10. Table 5.11 presents the overall risk level of mine calculated using equation 3.19.

Table 5.10 Improved risk levels with weights at the hazardous group level

Hazard group	Mine-1	Mine-2	Mine-3	Mine-4	Mine-5	Mine-6
	$RL_{HG1} \times W_1$	$RL_{HG2} \times W_2$	$RL_{HG3} \times W_3$	$RL_{HG4} \times W_4$	$RL_{HG5} \times W_5$	$RL_{HG6} \times W_6$
Ground movement	800.63	720.49	848.49	596.71	999.28	644.72
Transport machinery (non-winding)	408.85	633.18	540.04	393.58	397.52	437.18
Machinery other than transport machinery	264.09	267.68	360.23	294.09	256.05	349.49
Explosives	121.68	119.70	127.47	100.85	86.34	130.08
Electricity	24.62	87.99	46.99	45.10	52.98	28.29
Dust, gas and other combustible materials	995.69	579.67	460.52	730.36	1035.76	767.32
Other causes	131.95	120.61	100.27	116.02	124.00	120.94

Table 5.11 The overall risk level of the mines

Mine Name	Overall risk level in the mine
Mine-1	2747.51
Mine-2	2529.32
Mine-3	2484.01
Mine-4	2276.71
Mine-5	2951.93
Mine-6	2478.02

The comparison of risk level of hazard factors evaluated using the proposed methodology with the DGMS (2002) suggested rapid ranking method in mines is presented in Table 5.12. At the time of the study, the risk evaluation using the rapid ranking method was not completed in the mine-3 and mine-4.

Table 5.12 Comparison of risk levels evaluated using proposed methodology and rapid ranking method

Hazard group	Collected from							
	Mine-1	**TRAM**	**Mine-2**	**TRAM**	**Mine-5**	**TRAM**	**Mine-6**	**TRAM**
Ground movement	350	800.63	350	720.49	350	999.28	350	644.72
Transport machinery (non-winding)	175	408.85	175	633.18	350	397.52	175	437.18
Machinery other than transport machinery	75	264.09	35	267.68	350	256.05	350	349.49
Explosives	175	121.68	175	119.7	350	86.34	150	130.08
Electricity	175	24.62	35	87.99	350	52.98	350	28.29
Dust, gas and other combustible materials	350	995.69	350	579.67	350	1035.76	125	767.32
Other causes	5	131.95	350	120.61	350	124	350	120.94

5.4. Discussion

In this study, 7 hazard groups and 177 hazard events were identified from the accident data collected from the DGMS, observations in mines, FMEA and WRAC study, and literature survey. Questionnaires were designed from the identified hazards to evaluate the (i) risk parameters of the hazard events (ii) relative importance/weights of the risk parameters and (iii) relative importance/weights of the hazard factors. TRAM was developed to ease the calculations and reduce the man-hours required for risk analysis. Risk evaluation using TRAM involves (i) Mamdani fuzzy inference system for evaluating the risk levels of the hazard events (ii) VIKOR method for prioritizing the hazard events (iii) AHP method for evaluating relative importance of hazard groups and (iv) the synthesis module for ensuring that the risk analysis is being performed from the event level to group level and finally to overall mine level.

5.4.1. Risk estimation and prioritization at the hazardous event level

The risk levels of the hazard events calculated using the Mamdani fuzzy inference system are presented in Table 5.5. The risk levels of hazard groups at the group level are shown in Table 5.6. From Table 5.6, it is clear that the hazard group “dust, gas and other combustible materials” has the highest risk level and hazard group “electricity” has the lowest risk level in all the six mines.

The rankings of hazard events at the hazardous event level were presented in Table 5.7. The Q index values range from 0 to 1, in which 0 has the lowest risk and 1 has the highest risk. The ranking was done based on the Q index. The rank 1 has the highest risk associated with it when compared with the other ranks. From Table 5.7, one can observe that, in the hazard group “Ground movement”, the hazard event “geologically disturbed areas or weak old support” has the highest rank in all the six mines. In the hazard group “Transport machinery”, the hazard event “non-provision or improper maintenance of safety appliances” has the highest rank in mine-1, mine-3, mine-4, mine-5, and mine-6. “failure to inspect and maintain haulage road regularly” has the highest rank in mine-2. In the hazard group “Machinery other than transport machinery”, the hazard event “improper maintenance of engine room” has the highest rank in mine-1 and mine-6. “Workers standing around the machine” has the highest rank in mine-2, “deployment of unauthorized or untrained haulage engine operator” has the highest rank in mine-3, “improper oil tank condition” has the highest rank in mine-4, and “improper condition or maintenance of brakes” has the highest rank in mine-5. In the hazard group “Explosives”, the hazard event “failure to recover cartridge or detonator, in case of misfire” has the highest rank in mine-1, “drivage of joining gallery from both ends” has the highest rank in mine-2, and “failure to spray water before and after blasting” has the highest rank in mine-3, mine-4, mine-5 and mine-6. In the hazard group “Electricity”, the hazard event “improper maintenance of flameproof features of machinery” has the highest rank in mine-1, mine-4, mine-5, and mine-6, “failure to display danger boards on all electrical equipment’s” has the highest rank in mine-2, and “improper shutdown procedure” has the highest rank in mine-3. In the hazard group “Dust, gas and other combustible materials”, the hazard event “geological disturbance affecting panel" has the highest rank in mine-1, mine-5, and mine-6. "Improper monitoring of fire stoppings" has the highest rank in mine-2, "accumulation of coal dust at working panel and loading points" has the highest rank in mine-3, and "inadequate ventilation" has the highest rank in mine-4. In the hazard group "Other causes", the hazard event "presence of old water lodged area or abandoned workings" has the highest rank in mine-1, mine-2, and mine-5, and "working near geological disturbances" has the highest rank in mine-3, mine-4, and mine-6.

5.4.2. Risk evaluation at the hazardous group level and mine level

The determined relative importance of the hazard groups obtained using AHP method is shown in Table 5.8. The reformed risk levels at the hazardous group level are presented in Table 5.10. From Table 5.10, it is clear that the hazard group "dust, gas and other combustible materials" has the highest risk in mine-1, mine-4, mine-5, mine-6, and hazard group "electricity" has the lowest risk level in all the six mines. The risk level ranking order after considering weight contribution in mine-1, mine-4, and mine-5 is dust, gas and other combustible materials > ground movement > transport machinery (non-winding) > machinery other than transport machinery > other causes > explosives > electricity. There was a history of spontaneous heating and geological disturbances recorded in mine-1, mine-4, and mine-5. This justifies the highest rank to the hazard group "dust, gas and other combustible materials" in mine-1, mine-4, and mine-5. The risk level ranking order in mine-2 is ground movement > transport machinery (non-winding) > dust, gas and other combustible materials > machinery other than transport machinery > other causes > explosives > electricity. The risk level ranking order after considering weight contribution in mine-3 is ground movement > transport machinery (non-winding) > dust, gas and other combustible materials > machinery other than transport machinery > explosives > other causes > electricity. The risk level ranking order after considering weight contribution in mine-6 is dust, gas and other combustible materials > ground movement > transport machinery (non-winding) > machinery other than transport machinery > explosives > other causes > electricity.

From Table 5.11, it is clear that mine-5 has the highest risk level among the evaluated mines. The ranking order of the mines based on the overall risk level is mine-5 > mine-1 > mine-2 > mine-3 > mine-6 > mine-4. Based on the results the mine management should focus on the mine-5 to reduce the risk level of the mine. In mine-5, the primary importance should be given to dust, gas and other combustible materials, followed by ground movement, transport machinery (non-winding), machinery other than transport machinery, other causes, explosives, and electricity.

It can be seen from Table 5.12 that the risk level of hazard groups evaluated using the DGMS (2002) suggested rapid ranking method in mines have produced same risk level for multiple hazard groups, which makes it hard to prioritize. In mine-5, it is clear that the risk level of all the hazard groups have produced equal risk level (350). This contradicts the basic aim of the risk assessment process to evaluate, prioritize and implement control measures based on the evaluated risk value. Whereas the risk evaluated using the TRAM, have each hazard group with different risk level, which makes it easier to prioritize based on the risk level values.

From the results of the proposed methodology, it is clear that the prioritization can be done based on the risk level values evaluated at the hazardous event level, hazardous group level and overall mine level. The mines should allocate resources based on the order of risk rankings. As all the mines are subsidy of CIL, CIL should focus on mine-5 to reduce the risk level of the mine. Mine-1, mine-4, mine-5, and mine-6 should give priority to the hazard group “dust, gas and other combustible materials”, and mine-2, mine-3 should give priority to the hazard group “ground movement” to eliminate or mitigate the risk level of the hazard group. Correspondingly, all the six mines should give priority to the hazard event with the highest rank. These results will provide beneficial information to the safety officers, mine managers, mining engineers and other personnel to enhance safety management and establish safety standards as per the requirement. The results will also be helpful in preparing the safe operating practices and code of practices in mines. The proposed methodology possesses the following advantages over other qualitative and quantitative approaches:

- The hazard events with values of probability, exposure, and consequence are evaluated based on the rule base created.
- It is easy to evaluate and rank the hazard events, hazard groups and overall mines.
- The relative importance of the risk parameters and hazard groups are considered in the evaluation process.
- Linguistic expressions can be directly used for evaluation.

- Uncertain, imprecise or vague data and both qualitative and quantitative data can be used as inputs in the evaluation process.
- Precise output can be obtained.
- The computational time can be drastically reduced by using TRAM.

It can be foreseen that the proposed methodology could be utilized by not only mining engineers and safety officers but also for equipment designers and manufacturers. It can help them to focus on specific problem areas of the assessed equipment.

5.5. Chapter Summary

In this chapter, the development of hazard database, questionnaires, membership functions, rule base, and a GUI tool were presented. Citing the limitations of the qualitative and quantitative techniques, a methodology was proposed to evaluate the safety risks in underground coal mines. The analysis and results of the proposed methodology applied to six Indian underground coal mines were also discussed. From the results, it was found that the proposed methodology provides enhanced evaluation than the rapid ranking method. From the results, it was also found that each hazard event, hazard group, and overall mine has different ranking, which makes it easier to prioritize based on the ranking. The advantages of the proposed methodology and its implications to mines are also presented.

CHAPTER 6

CONCLUSIONS

In this thesis, FMEA, WRAC, FTA, and ETA approaches were applied to an underground coal mine (mine-1) to evaluate the safety risks in both qualitative and quantitative ways. Further, addressing the limitations of the qualitative and quantitative approaches, a methodology was proposed for safety risk assessment in underground coal mines. Based on the proposed methodology a user-friendly GUI was developed. The proposed methodology was applied to six underground coal mines to evaluate the safety risks in underground coal mines. The conclusions obtained from the present research investigations are summarized below:

- From the FMEA and WRAC analysis, it could be inferred that qualitative techniques are appropriate to evaluate safety risk in Indian underground mines. However, it could be noticed that the results produced are mainly subjective.
- From the FMEA and WRAC analysis, 41 hazards events related to 3 hazard groups, i.e. belt conveyor system, rope haulage system and LHD, and 115 hazard events related to 8 hazard groups, i.e. ground movement, rope haulage system, conveyor belt system, LHD, electricity, blasting, inundation, and dust, gas and other combustible materials were identified.
- The WRAC analysis revealed that out of 115 hazards identified, 20 hazards had low, 86 hazards had medium and 9 hazards had high risk levels.
- The limitations observed from the FMEA and WRAC analysis results were:
    - Different values of probability, exposure, and consequence ratings may produce the same value of risk value, but their hidden risk implications may be very different.
    - Multiple hazards have the same risk score and risk level, which makes it hard to prioritize.
- From the FTA and ETA analysis, it could be inferred that the quantitative analysis could not be performed in Indian underground coal mines in the existing conditions due to non-availability of risk parameters data.
- The ETA analysis revealed that it is hard to construct event tree for underground mines due to the presence of a large number of initiating events.

- The results of risk level of hazard events evaluated using Mamdani fuzzy inference system matched closely with the history of spontaneous heating and geological disturbances recorded in the mines. Therefore, Mamdani fuzzy inference system can be used evaluate the risk level of the hazard events in the Indian underground coal mines.
- The prioritization of hazard events at hazardous event level showed that VIKOR method provides better rankings as compared to FMEA and WRAC.
- AHP method was used to determine the relative importance. The relative importance of probability, exposure, consequence, and hazard groups was considered in the proposed methodology. The relative importance of the risk parameters was not considered in the evaluation of risk level using FMEA and WRAC.
- The evaluation of safety risks in six underground coal mines using the proposed methodology revealed that:
  - *At overall mine level:* mine-5 has the highest risk level among the evaluated mines.
  - *At hazardous group level:* dust, gas and other combustible materials has the highest risk level in mine-1, mine-4, mine-5, mine-6, and ground movement has the highest risk level in mine-2, mine-3.
- The comparison of risk levels of hazard groups indicated that the proposed methodology presents enhanced evaluation than DGMS (2002) proposed rapid ranking method.
- As the proposed methodology is generic in nature, it can be applied to all types of mines in the Indian mining industry.
- TRAM can be easily applied in the mines for evaluation of safety risks. TRAM reduced the computational time and increased the speed of the risk assessment process.
- TRAM can be applied to all the mines in the Indian mining industry by updating the hazard database in the TRAM, as per the requirement of the mine.
- The results obtained using the proposed methodology will be useful to the mine management in improving the safety in the workplace by helping in
  - Identifying unsafe acts, unsafe working methods, unsafe machinery, and an unsafe working environment.

- Developing safe operating procedures, code of practices, SMP, and control measures.
- Prioritizing the available resources based on the risk level of the hazards.
- Checking the existing safety standards within the mine.
- Reviewing high-risk areas, machinery or system in the mine.
- In applying appropriate risk treatment approach from hierarchy of controls.

6.1. Contributions of the Thesis

The contribution of the thesis can be listed as follows:

- Safety risk assessment technique aims to evaluate the hazards and control the hazards being evaluated based on the risk level. The use of rapid ranking technique and 5×5-risk matrix suggested by DGMS and CIL breaks the primary aim of the risk assessment by having multiple hazards with the same risk level or risk score. The proposed methodology provides the risk level and rankings for the hazard events, hazard groups and overall mine.
- The commonly used risk assessment techniques like FMEA, WRAC can only be used to evaluate single equipment or operation at a time, while the proposed methodology can be used to evaluate various equipment or operations at a time.
- 177 hazard events related to 7 hazard groups/factors, i.e. ground movement (fall of roof/ side), transport machinery (rope haulage, conveyor), machinery other than transport machinery (LHD, haulage engine), explosives (shot firing and blasting), electricity, dust, gas and other combustible materials, and other causes (inundation) of underground coal mines were identified.
- The current risk assessment techniques followed in the Indian coal mining industry like DGMS-Risk Matrix, ISO/CIL-Risk Matrix, DGMS/SCCL Risk Score (rapid ranking method) were also provided in the TRAM for enabling comparison with the proposed methodology.

6.2. Limitations and Future Scope of the Research

Although this study bridges a certain gap in the existing risk assessment approaches literature, it has some limitations as follows:

- FMEA was used to evaluate hazards related to mining equipment and machinery only.

- Individual hazard factors namely life-style, mental health, demographic, and socio-economic factors were not considered in this study.

The following are the directions for future research:

- Sensitivity analysis of the proposed methodology can be carried out.
- Bayesian network in Artificial intelligence can be employed in the proposed methodology to develop an advanced risk assessment approach.

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APPENDIX A: Questionnaires

Questionnaire

Hazard Evaluation Form

General Information

Full Name: __________________________________

Designation: __________________________________

Mine Name: __________________________________

Consequence: The most probable results of a potential accident	
Scale values	**Description**
C1	Small injury (Minor first aid)
C2	Minor (Temporary disability, many lost time injuries)
C3	Serious (Significant chance of fatality, permanent disability)
C4	Fatality (One fatality)
C5	Major fatality (A few fatalities, 1-4 fatalities)
C6	Catastrophic (Many fatalities, > 4 fatalities)

Exposure: Frequency of occurrence of the hazard-event	
Scale values	**Description**
E1	Very Rare (More than yearly)
E2	Rare (Yearly)
E3	Unusual (Monthly)
E4	Occasional (Weekly)
E5	Frequent (Daily)
E6	Continuous (Several times daily)

Probability: Chance that the personnel will be harmed	
Scale values	**Description**
P1	Practically impossible (One in 1000 years)
P2	Conceivable but possible (Once every 100 years)
P3	Only remotely possible (Once every thirty years)
P4	Unusual but possible (Once every ten years)
P5	Quite possible (Once every three years)
P6	May well be expected (Once a year)

GROUND MOVEMENT – ROOF AND SIDE FALLS

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

GM1. Rock Mass Rating not determined and Systematic Support Rules not framed properly

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM2. Poor knowledge of approved Systematic Support Rules

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM3. Poorly supported or unsupported roof

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM4. Lack of indicators in strata monitoring

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM5. Delay in supporting freshly exposed roof

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM6. Poor quality of cement capsules, bearing plates and drill rods

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM7. Less than adequate grout in the column

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM8. Unavailability of support material

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM9. Deployment of an unauthorized or untrained support crew

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM10. Poor supervision

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

GM11. Non vertical alignment of galleries

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

GM12. More height and width of galleries

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

GM13. Presence of subsidence cracks and fissures on surface above development panel

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

GM14. Improper testing and dressing

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

GM15. Geologically disturbed areas or weak old supports

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

GM16. Weak roof or sided conditions

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

GM17. Water seepage

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

Pairwise comparison for parameter weights

	Consequence	**Exposure**	**Probability**
Consequence			
Exposure			
Probability			

TRANSPORT MACHINERY (NON-WINDING) - ROPE HAULAGE

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

TM1. Deployment of an unauthorized or untrained trammer or clipman

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM2. Overloading of tubs

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM3. Defective or improper clips or lashing chain

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM4. Failure of drawbar

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM5. Unexpected movement of tubs

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM6. Improper laying and maintenance of track line

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM7. Improper maintenance of tubs and their fittings

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM8. Lack of precaution while haulage track line crosses travelling road

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM9. Defective rope, rope splicing, rope capel or shackles

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM10. Lack of proper illumination and white wash at coupling and uncoupling points

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM11. Improper signaling

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM12. Failure to display safety labels and code of signals at all stopping places along the roadway

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM13. Non-provision of safety buffers

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM14. Non-provision or improper maintenance of safety appliances like stop blocks, runway switches, backstay, drags, catches, safety hooks, jazz rails, friction rollers, re-railers

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM15. Failure of sprags

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM16. Failure to inspect and maintain haulage road regularly

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

Pairwise comparison for parameter weights

	Consequence	**Exposure**	**Probability**
Consequence			
Exposure			
Probability			

TRANSPORT MACHINERY (NON-WINDING) - CONVEYOR

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

TM17. Deployment of an unauthorized or untrained conveyor operator

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM18. Improper signalling by conveyor operator

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM19. Pre-start check not performed by the conveyor operator

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM20. Improper condition of belt and belt line

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM21. Irregular maintenance of a weak or damaged belt joint

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM22. Inadequate cleaning of spillage coal in belt sides, drive heads and tail ends

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM23. Inattentive chute opening and improper screen of chute

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM24. Breaking of coupling or bolts of coupling and non-provision of coupling guard

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM25. Non-provision of guards around drive head, tail end, and tensioning unit

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM26. Bearing failure of drive head

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM27. Friction in the running belt due to spillage coal and belt structure

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM28. Failure of pre-start alarm

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM29. Failure of pull cord and lock out switches

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM30. Operator wearing loose clothing

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM31. Cleaning belt or checking gear-box and coupling, while the conveyor is in motion

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM32. Failure to display safety labels and code of signals near the conveyor

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM33. Damaged idlers or rollers

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM34. Lack of proper illumination near drive head, discharge and tail end drums

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM35. Worker crossing the belt to the other side or Inadvertent entry of a worker while the belt is moving

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

TM36. Improper shovel for cleaning the coal near tail end drum

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MACHINERY OTHER THAN TRANSPORT MACHINERY – LHD / SDL

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

MM1. Deployment of an unauthorized or untrained operator

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM2. Pre-start check not performed by the operator

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM3. Front or rear light not working

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM4. Audio visual alarm or bell not working

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM5. Foot switch or dead man switch not working

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM6. Improper oil tank condition

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM7. Bad condition of tyres / crawler

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM8. Improper condition of parking or service brakes

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM9. Parking or standing of machine at a gradient

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM10. Improper condition of lift or tilt cylinder

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM11. Improper canopy or canopy not provided

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

MM12. Bypass dump valve or dump valve not in order

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM13. Non-provision of lock out warning tags on the machine

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM14. Poor condition of front or rear frame

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM15. Pilot switch not in order

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM16. Pressure relief valve not in order

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM17. Plying of machine in disturbed or unsafe areas

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM18. Temperature switch not in order

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM19. Workers standing around the machine or unexpected movement of a trailing cable

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM20. Poor condition of bucket

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM21. Oil leakage or damage of steering mechanism

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MM22. Improper condition of engine

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

MACHINERY OTHER THAN TRANSPORT MACHINERY – HAULAGE ENGINE

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

MM23. Deployment of an unauthorized or untrained haulage engine operator

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MM24. Improper maintenance of engine room

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MM25. Non-provision of guards around all moving parts

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MM26. Improper condition or maintenance of brakes

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MM27. Improper condition or maintenance of haulage engine

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MM28. Improper condition or maintenance of drum, surge wheel, clutch, and gears

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MM29. Improper condition of automatic catches and buffers

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

MM30. Non-functioning of speed limit switch and distance indicator

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

Pairwise comparison for parameter weights

	Consequence	**Exposure**	**Probability**
Consequence			
Exposure			
Probability			

EXPLOSIVES - SHOT FIRING AND BLASTING

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

SF1. Deployment of an unauthorized or untrained blasting crew

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF2. Non following of the blasting card system

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF3. Drivage of joining gallery from both ends

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF4. Priming of explosives in unauthorized places

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF5. Multiple operations at face while charging

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF6. Improper or poorly maintained blasting tools

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF7. Carrying of explosives and detonator together

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF8. Shot firing from a source other than the exploder

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF9. Shot firer engaged in other work

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF10. Improper drilling, cleaning, charging and stemming of shot holes

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF11. Failure to warn before blasting

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF12. Failure to spray water before and after blasting

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF13. Failure to cover entrance with fence, in case of misfire

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

SF14. Failure to recover cartridge or detonator, in case of misfire

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

Pairwise comparison for parameter weights

	Consequence	**Exposure**	**Probability**
Consequence			
Exposure			
Probability			

ELECTRICITY

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

EL1. Failure of protective devices

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL2. Improper earthing system or earth pit and neutral pit

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL3. Improper maintenance of flame proof features of machinery

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL4. Improper insulation of electric cables

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL5. Improper permanent cable joints (compounding)

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL6. Improper shutdown procedure

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL7. Improper fencing of installations

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL8. Faulty power cables

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL9. Improper maintenance of electric apparatus of equipment's (without proper precaution)

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL10. Housing of power cable along with signaling cable and lighting cable jointly

Consequence:	☐ C1	☐ C2	☐ C3	☐ C4	☐ C5	☐ C6
Exposure:	☐ E1	☐ E2	☐ E3	☐ E4	☐ E5	☐ E6
Probability:	☐ P1	☐ P2	☐ P3	☐ P4	☐ P5	☐ P6

EL11. Unsatisfactory flexible trailing cable

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EL12. Improper reeling or unreeling of trailing cable

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EL13. Failure to display danger boards on all electrical equipment's

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EL14. Failure to inspect all the electrical parts of the energized machines daily for frayed cords, induction, arcing

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EL15. Non-intrinsic signaling and telephonic communication circuits

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EL16. Improper condition of signaling wires and its clamping

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EL17. Improper condition of gate end circuit breaker

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EL18. Failure to connect plugs or sockets to gate end box

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

Pairwise comparison for parameter weights

	Consequence	**Exposure**	**Probability**
Consequence			
Exposure			
Probability			

DUST, GAS AND OTHER COMBUSTIBLE MATERIAL - EXPLOSION

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

EX1. Improper sealing of extracted panels

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX2. Leakage from sectionalisation stoppings

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX3. Inadequate or non-functioning of gas detecting apparatus

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX4. Deployment of untrained supervisors

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX5. Improper sampling of gases by supervisors

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX6. Non-inter coupling of underground power with the main mine ventilator fans

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX7. Gas cutting and welding work near a dusty area or any unauthorized area

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX8. Failure to provide sand and water near gas cutting and welding workplace

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX9. Stone dust barrier not provided at panel entry

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX10. Accumulation of coal dust at working panel and loading points

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX11. Non-provision of explosion proof stoppings where CH_4 exceeds 2%

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX12. Improper monitoring or inspection of gases in sealed off areas and old working areas which are not sealed off

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX13. Failure to examine rate of emission of gas every month

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX14. Contrabands

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX15. Presence of fissures, surface cracks, subsidence

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX16. Irregular stone dusting

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6

Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6

Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

DUST, GAS AND OTHER COMBUSTIBLE MATERIAL - VENTILATION

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

EX17. Insufficient fan capacity

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX18. Inadequate ventilation

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX19. Non availability or improper condition of auxiliary fans

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX20. Blind heading

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX21. Heat and humidity

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX22. Lengthy ventilation route

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX23. Irregular ventilation survey

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX24. Obstruction of the return airway or insufficient intake

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX25. Improper condition or maintenance of main mechanical ventilator

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX26. Leakage in ducts

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX27. Lack of dust suppression arrangements

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX28. Non-provision of interlocking arrangement of auxiliary fans

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX29. Improper condition or maintenance of stoppings

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX30. Non-provision of a fire resistant mechanical ventilator, ducts, ventilation doors and air crossings

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX31. Failure to check speed, amperage and fan drift

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX32. Non-provision or improper maintenance of firefighting equipment's

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX33. Non-provision of access for the inspection of stoppings, doors, airways and air crossing

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX34. Failure to clean fallen coal or debris in return airway

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

EX35. Improper condition or maintenance of safety lamp

Consequence:	☐	C1	☐	C2	☐	C3	☐	C4	☐	C5	☐	C6
Exposure:	☐	E1	☐	E2	☐	E3	☐	E4	☐	E5	☐	E6
Probability:	☐	P1	☐	P2	☐	P3	☐	P4	☐	P5	☐	P6

DUST, GAS AND OTHER COMBUSTIBLE MATERIAL - MINE FIRE

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

EX36. Susceptibility of spontaneous heating due to low Cross Point Temperature and high moisture content

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX37. Shallow depth of cover

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX38. Huge depillared area

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX39. Geological disturbance affecting panel

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX40. Thick seam

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX41. Failure to clean fallen coal, wood cuttings, oil and greasy waste

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX42. Improper panel size

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX43. Improper monitoring of fire stoppings

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

EX44. Improper early fire detection system

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

Pairwise comparison for parameter weights

	Consequence	**Exposure**	**Probability**
Consequence			
Exposure			
Probability			

OTHER CAUSES - INUNDATION

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

OC1. Inaccurate drivage of face

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC2. Insufficient number of pumps or failure of pumps

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC3. Working near geological disturbance, i.e. faults, folds, slips etc.

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC4. Presence of surface cracks, fissures, subsidence

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC5. Old borehole which are not sealed effectively

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC6. Borehole not marked in underground plan

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC7. Unexpected heavy rains and power failure

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC8. Failure of barriers

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC9. Non-provision of side drains

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC10. Insufficient sump area

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC11. Failure of water dams

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC12. Failure to prepare and regularly update water danger plan

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC13. Presence of old water lodged area or abandoned workings

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OTHER CAUSES – UNCLASSIFIED

Please select (√) the appropriate Consequence, Exposure and Probability scales for the following hazards

OC14. Non-provision of personal protective equipment's to workers

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC15. Workers not wearing personal protective equipment's

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC16. Failure to prepare or distribute Safe Operating Procedure documents

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC17. Failure of telephone communication system or signaling system

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

OC18. Improper or faulty surveying of workings

Consequence: ☐ C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6
Exposure: ☐ E1 ☐ E2 ☐ E3 ☐ E4 ☐ E5 ☐ E6
Probability: ☐ P1 ☐ P2 ☐ P3 ☐ P4 ☐ P5 ☐ P6

Pairwise comparison for parameter weights

	Consequence	**Exposure**	**Probability**
Consequence			
Exposure			
Probability			

APPENDIX B: AHP Questionnaire

Intensity of importance in sub criteria	Explanation	Scale
Equal Importance	Two hazard factor contribute equally	1
Between equal importance and weak importance	When compromise is needed	2
Weak importance	Experience and judgment slightly favour one hazard factor over another	3
Between weak and strong importance	When compromise is needed	4
Strong importance	Experience and judgment strongly favour one hazard factor over another	5
Between strong and very strong importance	When compromise is needed	6
Very strong importance	A hazard factor is favoured very strongly over another.	7
Between very strong and absolute importance	When compromise is needed	8
Absolute importance	One hazard factor over another is of the highest possible affirmation	9

Pairwise Comparison

	Ground movement (fall of roof/ side)	Transport machinery (rope haulage, conveyor)	Machinery other than transport machinery	Explosives (shot firing and blasting)	Electricity	Dust, gas and other combustible materials	Other causes (inundation)
Ground movement (fall of roof/ side)	1						
Transport machinery (rope haulage, conveyor)		1					
Machinery other than transport machinery (LHD, SDL, haulage engine)			1				
Explosives (shot firing and blasting)				1			
Electricity					1		
Dust, gas and other combustible materials						1	
Other causes (inundation)							1

APPENDIX C: Fuzzy Rule Base

In index format: <input MFs>, <output MFs>, (<weight>) : <logical operator - 1(AND), 2(OR)>

1 1 1, 1 (1) : 1	2 1 1, 1 (1) : 1	3 1 1, 1 (1) : 1	4 1 1, 1 (1) : 1	5 1 1, 1 (1) : 1	6 1 1, 1 (1) : 1
1 1 2, 1 (1) : 1	2 1 2, 1 (1) : 1	3 1 2, 1 (1) : 1	4 1 2, 1 (1) : 1	5 1 2, 1 (1) : 1	6 1 2, 1 (1) : 1
1 1 3, 1 (1) : 1	2 1 3, 1 (1) : 1	3 1 3, 1 (1) : 1	4 1 3, 1 (1) : 1	5 1 3, 1 (1) : 1	6 1 3, 2 (1) : 1
1 1 4, 1 (1) : 1	2 1 4, 1 (1) : 1	3 1 4, 1 (1) : 1	4 1 4, 1 (1) : 1	5 1 4, 1 (1) : 1	6 1 4, 2 (1) : 1
1 1 5, 1 (1) : 1	2 1 5, 1 (1) : 1	3 1 5, 1 (1) : 1	4 1 5, 1 (1) : 1	5 1 5, 2 (1) : 1	6 1 5, 3 (1) : 1
1 1 6, 1 (1) : 1	2 1 6, 1 (1) : 1	3 1 6, 1 (1) : 1	4 1 6, 1 (1) : 1	5 1 6, 2 (1) : 1	6 1 6, 3 (1) : 1
1 2 1, 1 (1) : 1	2 2 1, 1 (1) : 1	3 2 1, 1 (1) : 1	4 2 1, 1 (1) : 1	5 2 1, 1 (1) : 1	6 2 1, 1 (1) : 1
1 2 2, 1 (1) : 1	2 2 2, 1 (1) : 1	3 2 2, 1 (1) : 1	4 2 2, 1 (1) : 1	5 2 2, 1 (1) : 1	6 2 2, 1 (1) : 1
1 2 3, 1 (1) : 1	2 2 3, 1 (1) : 1	3 2 3, 1 (1) : 1	4 2 3, 1 (1) : 1	5 2 3, 1 (1) : 1	6 2 3, 2 (1) : 1
1 2 4, 1 (1) : 1	2 2 4, 1 (1) : 1	3 2 4, 1 (1) : 1	4 2 4, 1 (1) : 1	5 2 4, 1 (1) : 1	6 2 4, 2 (1) : 1
1 2 5, 1 (1) : 1	2 2 5, 1 (1) : 1	3 2 5, 1 (1) : 1	4 2 5, 2 (1) : 1	5 2 5, 2 (1) : 1	6 2 5, 3 (1) : 1
1 2 6, 1 (1) : 1	2 2 6, 1 (1) : 1	3 2 6, 1 (1) : 1	4 2 6, 2 (1) : 1	5 2 6, 2 (1) : 1	6 2 6, 3 (1) : 1
1 3 1, 1 (1) : 1	2 3 1, 1 (1) : 1	3 3 1, 1 (1) : 1	4 3 1, 1 (1) : 1	5 3 1, 1 (1) : 1	6 3 1, 1 (1) : 1
1 3 2, 1 (1) : 1	2 3 2, 1 (1) : 1	3 3 2, 1 (1) : 1	4 3 2, 1 (1) : 1	5 3 2, 1 (1) : 1	6 3 2, 2 (1) : 1
1 3 3, 1 (1) : 1	2 3 3, 1 (1) : 1	3 3 3, 1 (1) : 1	4 3 3, 1 (1) : 1	5 3 3, 1 (1) : 1	6 3 3, 2 (1) : 1
1 3 4, 1 (1) : 1	2 3 4, 1 (1) : 1	3 3 4, 1 (1) : 1	4 3 4, 1 (1) : 1	5 3 4, 2 (1) : 1	6 3 4, 3 (1) : 1
1 3 5, 1 (1) : 1	2 3 5, 2 (1) : 1	3 3 5, 1 (1) : 1	4 3 5, 2 (1) : 1	5 3 5, 2 (1) : 1	6 3 5, 3 (1) : 1
1 3 6, 1 (1) : 1	2 3 6, 2 (1) : 1	3 3 6, 1 (1) : 1	4 3 6, 2 (1) : 1	5 3 6, 2 (1) : 1	6 3 6, 3 (1) : 1
1 4 1, 1 (1) : 1	2 4 1, 1 (1) : 1	3 4 1, 1 (1) : 1	4 4 1, 1 (1) : 1	5 4 1, 1 (1) : 1	6 4 1, 2 (1) : 1
1 4 2, 1 (1) : 1	2 4 2, 1 (1) : 1	3 4 2, 1 (1) : 1	4 4 2, 1 (1) : 1	5 4 2, 1 (1) : 1	6 4 2, 2 (1) : 1
1 4 3, 1 (1) : 1	2 4 3, 1 (1) : 1	3 4 3, 1 (1) : 1	4 4 3, 1 (1) : 1	5 4 3, 2 (1) : 1	6 4 3, 2 (1) : 1
1 4 4, 1 (1) : 1	2 4 4, 1 (1) : 1	3 4 4, 1 (1) : 1	4 4 4, 2 (1) : 1	5 4 4, 2 (1) : 1	6 4 4, 3 (1) : 1
1 4 5, 1 (1) : 1	2 4 5, 2 (1) : 1	3 4 5, 2 (1) : 1	4 4 5, 2 (1) : 1	5 4 5, 3 (1) : 1	6 4 5, 3 (1) : 1
1 4 6, 1 (1) : 1	2 4 6, 2 (1) : 1	3 4 6, 2 (1) : 1	4 4 6, 2 (1) : 1	5 4 6, 3 (1) : 1	6 4 6, 3 (1) : 1
1 5 1, 1 (1) : 1	2 5 1, 1 (1) : 1	3 5 1, 1 (1) : 1	4 5 1, 1 (1) : 1	5 5 1, 1 (1) : 1	6 5 1, 2 (1) : 1
1 5 2, 1 (1) : 1	2 5 2, 1 (1) : 1	3 5 2, 1 (1) : 1	4 5 2, 1 (1) : 1	5 5 2, 2 (1) : 1	6 5 2, 2 (1) : 1
1 5 3, 1 (1) : 1	2 5 3, 1 (1) : 1	3 5 3, 1 (1) : 1	4 5 3, 1 (1) : 1	5 5 3, 2 (1) : 1	6 5 3, 3 (1) : 1
1 5 4, 1 (1) : 1	2 5 4, 1 (1) : 1	3 5 4, 1 (1) : 1	4 5 4, 2 (1) : 1	5 5 4, 2 (1) : 1	6 5 4, 3 (1) : 1
1 5 5, 2 (1) : 1	2 5 5, 2 (1) : 1	3 5 5, 2 (1) : 1	4 5 5, 2 (1) : 1	5 5 5, 3 (1) : 1	6 5 5, 3 (1) : 1
1 5 6, 2 (1) : 1	2 5 6, 2 (1) : 1	3 5 6, 2 (1) : 1	4 5 6, 2 (1) : 1	5 5 6, 3 (1) : 1	6 5 6, 3 (1) : 1
1 6 1, 1 (1) : 1	2 6 1, 1 (1) : 1	3 6 1, 1 (1) : 1	4 6 1, 1 (1) : 1	5 6 1, 2 (1) : 1	6 6 1, 2 (1) : 1
1 6 2, 1 (1) : 1	2 6 2, 1 (1) : 1	3 6 2, 1 (1) : 1	4 6 2, 1 (1) : 1	5 6 2, 2 (1) : 1	6 6 2, 3 (1) : 1
1 6 3, 1 (1) : 1	2 6 3, 1 (1) : 1	3 6 3, 1 (1) : 1	4 6 3, 1 (1) : 1	5 6 3, 2 (1) : 1	6 6 3, 3 (1) : 1
1 6 4, 1 (1) : 1	2 6 4, 1 (1) : 1	3 6 4, 1 (1) : 1	4 6 4, 2 (1) : 1	5 6 4, 3 (1) : 1	6 6 4, 3 (1) : 1
1 6 5, 2 (1) : 1	2 6 5, 2 (1) : 1	3 6 5, 2 (1) : 1	4 6 5, 2 (1) : 1	5 6 5, 3 (1) : 1	6 6 5, 3 (1) : 1
1 6 6, 2 (1) : 1	2 6 6, 2 (1) : 1	3 6 6, 2 (1) : 1	4 6 6, 3 (1) : 1	5 6 6, 3 (1) : 1	6 6 6, 3 (1) : 1

APPENDIX D: Defuzzified Experts' Opinion Collected from the Mines

Table D1. Defuzzified experts' opinion collected from the mine-1

Hazard number	C	E	P
Ground movement – Roof and side fall			
GM1	3.79	3.49	7.00
GM2	3.54	7.08	5.92
GM3	3.75	6.75	7.75
GM4	2.07	4.08	7.17
GM5	3.38	6.04	6.33
GM6	2.76	4.36	6.33
GM7	2.72	4.33	7.17
GM8	3.25	4.17	7.00
GM9	2.55	3.90	6.58
GM10	2.40	3.90	6.00
GM11	3.38	3.69	5.92
GM12	1.69	4.07	5.92
GM13	4.08	6.68	7.58
GM14	2.35	5.60	7.92
GM15	4.17	8.25	7.75
GM16	3.00	5.63	6.83
GM17	2.42	3.68	5.92
Risk factors weights	**0.12**	**0.65**	**0.23**
Transport machinery (non-winding) - Rope haulage and conveyor			
TM1	2.08	3.75	7.13
TM2	1.98	2.33	6.88
TM3	1.81	2.71	7.50
TM4	2.27	2.48	7.00
TM5	3.19	3.29	6.75
TM6	3.19	2.71	6.88
TM7	1.95	3.52	7.38
TM8	2.32	5.50	8.13
TM9	1.92	3.69	6.75
TM10	1.91	3.13	6.63
TM11	3.09	2.17	5.50
TM12	3.44	2.48	7.63
TM13	1.75	3.94	7.38
TM14	3.69	4.83	7.38
TM15	2.27	5.17	7.50
TM16	2.51	6.65	6.75
TM17	3.00	4.65	6.59
TM18	2.71	3.88	5.41
TM19	2.25	3.24	6.00

TM20	2.66	4.33	7.29
TM21	2.34	3.00	5.53
TM22	2.76	3.24	6.59
TM23	2.66	3.43	5.29
TM24	2.42	2.73	5.76
TM25	2.58	3.22	6.12
TM26	2.27	3.45	5.88
TM27	3.65	5.37	6.47
TM28	2.88	2.75	5.29
TM29	2.83	3.69	6.82
TM30	2.83	4.04	7.06
TM31	2.59	4.33	6.59
TM32	2.26	3.78	6.24
TM33	1.96	3.16	5.88
TM34	2.36	4.59	6.24
TM35	2.82	3.63	6.35
TM36	2.79	3.59	5.41
Risk factors weights	**0.65**	**0.11**	**0.24**
Machinery other than transport machinery - LHD, Haulage engine			
MM1	2.76	3.57	6.24
MM2	2.19	3.90	6.94
MM3	3.24	2.90	6.00
MM4	2.88	2.49	5.65
MM5	3.47	2.47	6.00
MM6	4.18	2.35	5.65
MM7	2.11	2.16	6.71
MM8	3.29	2.90	7.18
MM9	3.29	2.88	7.06
MM10	2.09	3.51	7.18
MM11	2.77	3.00	6.14
MM12	2.83	2.29	5.88
MM13	2.90	3.82	8.00
MM14	2.11	3.51	6.12
MM15	1.75	3.57	7.76
MM16	2.88	3.57	5.33
MM17	2.78	2.27	5.29
MM18	2.10	2.63	5.88
MM19	3.12	4.06	7.53
MM20	3.06	2.71	6.59
MM21	3.82	2.25	4.61
MM22	2.71	3.02	7.18
MM23	2.84	4.75	5.76
MM24	2.89	5.45	6.71
MM25	2.78	4.96	6.47

MM26	4.00	4.94	6.94
MM27	3.82	4.00	6.47
MM28	3.06	3.61	6.71
MM29	3.47	3.45	4.73
MM30	2.95	3.08	5.33
Risk factors weights	**0.12**	**0.67**	**0.21**
Explosives - Shot firing and blasting			
SF1	3.56	3.19	5.56
SF2	2.94	3.06	5.67
SF3	3.33	3.02	4.67
SF4	3.61	3.06	6.56
SF5	3.61	2.65	5.22
SF6	3.44	3.17	5.56
SF7	3.11	2.78	5.67
SF8	2.63	2.63	5.13
SF9	2.65	2.78	5.33
SF10	2.83	3.02	5.00
SF11	3.33	2.85	5.11
SF12	3.44	3.39	5.56
SF13	3.50	3.28	4.91
SF14	3.83	3.44	5.56
Risk factors weights	**0.62**	**0.18**	**0.20**
Electricity			
EL1	2.63	2.33	5.71
EL2	2.91	2.59	5.81
EL3	3.29	3.06	5.90
EL4	2.67	2.30	5.71
EL5	2.63	3.30	6.38
EL6	3.19	2.89	5.24
EL7	1.84	2.06	5.81
EL8	2.22	4.29	6.19
EL9	1.91	3.10	5.81
EL10	2.58	2.56	5.62
EL11	2.67	2.54	6.00
EL12	2.90	3.11	5.43
EL13	2.68	2.48	5.43
EL14	2.44	1.86	6.57
EL15	2.82	2.43	5.52
EL16	2.86	2.49	5.81
EL17	2.22	2.37	6.00
EL18	2.67	2.49	5.52
Risk factors weights	**0.70**	**0.15**	**0.15**
Dust, gas and other combustible materials – Explosion, ventilation, mine fire			
EX1	4.16	4.16	7.26

EX2	3.89	3.42	7.05
EX3	4.00	3.96	7.89
EX4	3.74	4.35	7.58
EX5	3.95	4.96	6.84
EX6	4.16	3.70	6.95
EX7	3.63	3.44	6.11
EX8	3.37	4.14	7.68
EX9	3.74	5.00	7.05
EX10	3.84	5.81	8.11
EX11	4.00	4.07	6.84
EX12	4.05	4.19	7.58
EX13	4.00	3.00	7.37
EX14	3.42	3.93	6.74
EX15	3.95	5.05	7.89
EX16	3.79	5.28	7.26
EX17	3.68	2.39	4.95
EX18	4.00	2.98	6.42
EX19	4.63	3.11	6.21
EX20	3.89	3.35	6.53
EX21	2.86	3.89	6.11
EX22	3.32	3.18	5.68
EX23	3.89	4.02	7.05
EX24	3.63	2.09	5.05
EX25	3.26	2.84	6.74
EX26	3.27	4.19	6.42
EX27	3.58	2.65	6.11
EX28	3.79	2.96	5.58
EX29	3.58	2.61	6.21
EX30	3.95	2.47	4.95
EX31	3.68	2.58	5.68
EX32	4.21	3.46	5.58
EX33	3.74	3.93	5.68
EX34	4.11	3.67	6.21
EX35	2.96	3.23	5.37
EX36	4.05	4.82	6.42
EX37	3.47	4.91	7.47
EX38	3.47	6.04	7.37
EX39	4.32	6.02	7.16
EX40	3.53	3.42	6.44
EX41	3.84	5.51	6.95
EX42	3.84	5.25	7.47
EX43	4.00	5.21	6.74
EX44	3.79	4.82	7.26
Risk factors weights	**0.16**	**0.62**	**0.22**

Other causes – Inundation, Unclassified			
OC1	3.25	3.59	6.48
OC2	2.86	2.67	6.00
OC3	3.71	4.48	7.62
OC4	3.52	3.73	6.95
OC5	3.43	2.94	6.67
OC6	2.97	3.00	6.57
OC7	4.00	2.68	5.75
OC8	3.10	3.46	6.19
OC9	3.43	2.03	6.67
OC10	3.43	4.19	6.86
OC11	4.19	4.60	5.90
OC12	3.76	3.68	6.00
OC13	4.33	4.89	7.14
OC14	3.43	3.63	6.95
OC15	2.41	3.38	6.86
OC16	2.72	4.90	7.52
OC17	3.43	4.05	5.83
OC18	3.40	4.84	6.93
Risk factors weights	**0.12**	**0.63**	**0.25**

Table D2. Defuzzified experts' opinion collected from the mine-2

Hazard number	C	E	P
Ground movement – Roof and side fall			
GM1	3.94	3.44	7.88
GM2	3.31	6.40	6.50
GM3	3.13	6.19	7.75
GM4	2.39	4.27	6.75
GM5	3.88	6.88	6.63
GM6	2.75	4.04	5.88
GM7	2.56	3.31	6.38
GM8	3.38	3.92	6.13
GM9	2.64	3.04	6.75
GM10	2.08	3.19	6.50
GM11	3.63	3.88	5.38
GM12	1.98	3.77	6.13
GM13	3.70	6.38	8.13
GM14	2.75	4.69	7.25
GM15	4.38	7.00	8.00
GM16	3.25	5.15	7.25
GM17	2.59	3.83	5.88
Risk factors weights	**0.09**	**0.69**	**0.22**
Transport machinery (non-winding) - Rope haulage and conveyor			
TM1	2.32	3.60	7.58
TM2	1.90	2.28	6.84
TM3	1.93	3.40	7.47
TM4	2.33	2.07	6.53
TM5	2.90	3.12	6.74
TM6	3.21	2.40	7.47
TM7	1.86	3.53	7.37
TM8	1.94	5.33	7.58
TM9	2.18	3.61	7.26
TM10	1.81	2.95	7.79
TM11	3.33	2.67	6.00
TM12	2.80	2.28	7.79
TM13	1.76	3.96	7.79
TM14	3.63	4.98	7.26
TM15	2.32	4.74	7.37
TM16	1.99	6.84	7.37
TM17	2.71	4.04	5.28
TM18	2.35	3.65	5.16
TM19	2.42	3.44	6.23
TM20	2.60	4.30	8.21
TM21	2.22	3.26	5.16
TM22	2.69	3.53	7.37

TM23	2.49	3.28	5.26
TM24	2.53	3.70	5.37
TM25	2.24	3.42	6.32
TM26	2.32	2.91	6.32
TM27	3.05	5.21	6.00
TM28	3.21	3.82	5.58
TM29	2.53	3.72	7.68
TM30	3.37	4.47	7.89
TM31	2.84	4.07	6.63
TM32	2.33	3.96	7.05
TM33	2.32	3.39	5.58
TM34	2.18	4.93	5.89
TM35	2.58	2.88	5.68
TM36	2.59	3.02	4.96
Risk factors weights	**0.19**	**0.61**	**0.20**
Machinery other than transport machinery - LHD, Haulage engine			
MM1	2.74	3.60	7.05
MM2	1.88	3.77	7.05
MM3	3.37	3.28	6.00
MM4	2.63	1.98	6.11
MM5	3.21	2.39	6.32
MM6	4.00	2.32	6.53
MM7	1.96	2.67	6.32
MM8	3.11	2.19	7.58
MM9	3.21	2.63	7.47
MM10	1.90	3.84	6.95
MM11	2.39	2.44	6.42
MM12	2.64	2.30	5.68
MM13	3.26	3.70	7.89
MM14	1.49	3.18	7.05
MM15	1.89	3.72	8.00
MM16	2.54	3.46	6.11
MM17	2.80	2.72	5.39
MM18	2.07	2.81	5.68
MM19	2.95	4.68	8.42
MM20	2.75	3.07	6.63
MM21	3.79	3.32	5.47
MM22	2.75	3.33	7.16
MM23	2.96	5.65	7.16
MM24	2.59	5.53	7.68
MM25	2.54	4.65	7.05
MM26	3.79	4.07	6.63
MM27	3.53	3.47	5.79
MM28	3.05	3.16	6.53

MM29	3.16	2.28	5.16
MM30	3.11	2.95	6.12
Risk factors weights	**0.13**	**0.32**	**0.55**
Explosives - Shot firing and blasting			
SF1	3.75	2.79	5.00
SF2	2.88	2.52	5.75
SF3	3.88	3.02	5.00
SF4	3.13	3.33	6.38
SF5	3.44	2.92	5.88
SF6	3.50	3.90	5.75
SF7	3.31	2.60	5.75
SF8	2.76	2.94	4.50
SF9	2.67	2.04	5.13
SF10	2.94	2.71	5.25
SF11	3.44	2.56	5.27
SF12	3.31	3.17	5.15
SF13	3.25	2.90	5.40
SF14	3.75	3.42	4.75
Risk factors weights	**0.63**	**0.11**	**0.26**
Electricity			
EL1	2.94	2.83	6.13
EL2	3.06	2.42	5.88
EL3	3.44	3.02	6.13
EL4	3.06	2.92	6.38
EL5	2.52	3.60	6.75
EL6	3.13	4.00	6.75
EL7	2.22	2.02	6.00
EL8	2.51	3.81	5.88
EL9	2.40	4.00	6.00
EL10	3.00	2.98	5.00
EL11	3.00	2.85	6.25
EL12	3.00	3.48	6.00
EL13	3.20	4.13	7.13
EL14	2.11	2.54	6.50
EL15	2.77	2.33	5.75
EL16	2.67	3.00	5.38
EL17	2.56	2.94	6.25
EL18	3.00	3.00	5.63
Risk factors weights	**0.30**	**0.22**	**0.48**
Dust, gas and other combustible materials – Explosion, ventilation, mine fire			
EX1	3.93	4.16	6.67
EX2	4.20	3.16	6.93
EX3	3.93	4.04	7.07
EX4	3.80	4.33	8.00

EX5	3.73	4.22	7.87
EX6	4.00	3.73	6.67
EX7	3.33	3.16	5.87
EX8	3.40	3.47	8.13
EX9	3.60	5.07	7.87
EX10	3.53	5.20	8.13
EX11	3.87	4.22	6.93
EX12	4.13	3.00	7.33
EX13	3.80	2.51	7.20
EX14	3.47	3.98	7.73
EX15	4.27	4.98	7.47
EX16	3.87	4.07	7.87
EX17	3.73	2.62	5.20
EX18	4.20	3.80	6.40
EX19	4.20	3.07	5.87
EX20	3.80	3.60	7.07
EX21	2.31	4.07	5.47
EX22	2.92	3.44	5.60
EX23	3.53	3.47	6.93
EX24	3.67	2.98	6.00
EX25	3.47	3.09	7.73
EX26	2.81	3.71	6.67
EX27	3.33	2.60	6.27
EX28	3.87	2.02	5.60
EX29	3.33	2.62	6.40
EX30	3.93	2.69	4.93
EX31	3.87	2.62	6.00
EX32	4.53	3.18	6.00
EX33	3.73	2.96	6.13
EX34	4.33	3.93	6.13
EX35	2.69	2.53	5.33
EX36	4.33	5.38	5.87
EX37	3.27	5.00	7.07
EX38	3.40	6.40	6.67
EX39	4.13	5.64	7.20
EX40	3.27	2.00	6.40
EX41	3.87	5.36	7.33
EX42	3.73	4.51	7.07
EX43	4.40	5.31	6.80
EX44	4.13	5.38	7.47
Risk factors weights	**0.59**	**0.28**	**0.13**
Other causes – Inundation, Unclassified			
OC1	3.20	4.46	7.00
OC2	3.13	2.73	4.63

OC3	3.50	5.21	7.63
OC4	3.94	3.85	7.25
OC5	3.44	2.92	5.88
OC6	2.94	3.69	5.88
OC7	3.63	2.90	5.75
OC8	2.85	3.75	5.77
OC9	3.56	2.35	6.38
OC10	3.69	4.23	7.00
OC11	4.00	4.58	5.77
OC12	3.63	3.81	5.77
OC13	4.31	5.46	7.63
OC14	3.69	4.19	6.75
OC15	2.24	2.71	6.50
OC16	2.75	5.06	7.75
OC17	3.64	3.96	5.38
OC18	4.00	5.43	6.60
Risk factors weights	**0.10**	**0.67**	**0.23**

Table D3. Defuzzified experts' opinion collected from the mine-3

Hazard number	C	E	P
Ground movement – Roof and side fall			
GM1	4.13	3.51	7.60
GM2	3.00	6.53	6.67
GM3	3.00	6.53	7.87
GM4	2.48	4.91	6.53
GM5	3.40	6.13	7.07
GM6	2.53	4.09	6.40
GM7	2.53	4.40	6.93
GM8	2.87	4.91	6.13
GM9	2.53	4.20	6.80
GM10	2.53	4.44	6.67
GM11	3.47	4.27	5.87
GM12	2.09	4.76	6.40
GM13	3.40	5.87	7.60
GM14	2.33	5.36	6.93
GM15	3.93	6.80	7.20
GM16	3.13	4.96	7.07
GM17	2.23	4.56	6.56
Risk factors weights	**0.11**	**0.65**	**0.24**
Transport machinery (non-winding) - Rope haulage and conveyor			
TM1	2.12	4.62	6.57
TM2	2.44	3.35	6.57
TM3	1.79	2.95	6.00
TM4	2.37	3.65	6.48
TM5	3.24	4.59	6.95
TM6	3.39	3.33	6.10
TM7	2.05	4.41	6.76
TM8	2.35	4.86	7.71
TM9	2.17	4.46	6.00
TM10	2.13	4.30	6.48
TM11	2.86	2.68	5.16
TM12	3.14	3.75	6.76
TM13	2.03	4.92	5.90
TM14	3.71	5.06	7.14
TM15	2.27	4.14	7.05
TM16	2.21	6.00	6.57
TM17	2.78	3.54	6.10
TM18	2.36	3.32	6.48
TM19	2.45	3.49	6.67
TM20	2.15	4.11	6.57
TM21	1.56	2.41	5.81
TM22	2.63	3.17	6.38

TM23	2.16	4.00	4.95
TM24	2.13	2.46	5.43
TM25	2.76	4.35	5.52
TM26	1.87	3.78	5.81
TM27	3.06	4.75	5.90
TM28	2.90	2.70	5.81
TM29	3.05	3.90	5.90
TM30	2.20	4.87	6.19
TM31	2.34	4.44	6.10
TM32	1.79	4.25	6.00
TM33	1.49	3.48	5.71
TM34	2.52	4.11	5.81
TM35	2.53	3.52	5.90
TM36	2.69	3.98	5.43
Risk factors weights	**0.62**	**0.19**	**0.19**
Machinery other than transport machinery - SDL, Haulage engine			
MM1	3.10	3.19	6.38
MM2	2.45	3.68	6.86
MM3	3.00	3.02	5.43
MM4	2.82	2.94	5.33
MM5	3.67	3.24	5.63
MM6	3.38	3.03	5.81
MM7	2.37	2.76	6.10
MM8	3.19	3.37	6.10
MM9	3.62	4.37	6.57
MM10	2.63	4.17	6.29
MM11	2.56	2.67	5.71
MM12	2.50	2.56	5.81
MM13	2.37	4.22	7.05
MM14	2.44	3.25	6.00
MM15	2.48	4.03	7.62
MM16	2.95	3.56	5.44
MM17	3.10	3.40	5.71
MM18	2.36	2.81	5.33
MM19	3.19	3.92	6.29
MM20	3.24	3.38	6.19
MM21	3.33	2.73	5.14
MM22	3.38	3.16	6.19
MM23	2.87	5.94	5.81
MM24	2.71	5.06	7.52
MM25	3.02	5.35	6.38
MM26	4.19	5.00	6.10
MM27	3.81	3.95	6.38
MM28	3.29	4.00	6.29

MM29	3.62	3.52	5.71
MM30	3.34	2.52	5.25
Risk factors weights	**0.13**	**0.67**	**0.20**
Explosives - Shot firing and blasting			
SF1	3.67	3.33	5.20
SF2	3.00	3.18	5.73
SF3	3.73	3.40	5.87
SF4	3.20	3.56	6.27
SF5	3.67	3.29	5.87
SF6	3.00	3.33	5.87
SF7	3.33	3.18	6.27
SF8	2.61	2.64	6.27
SF9	2.81	2.27	6.13
SF10	2.94	3.56	6.00
SF11	3.40	3.09	5.09
SF12	3.87	3.71	6.27
SF13	3.27	3.49	6.13
SF14	3.33	3.73	5.89
Risk factors weights	**0.60**	**0.29**	**0.11**
Electricity			
EL1	2.63	2.85	5.56
EL2	3.00	2.69	5.89
EL3	3.44	3.93	5.44
EL4	2.56	3.09	5.91
EL5	2.73	3.94	6.11
EL6	3.44	4.43	5.89
EL7	2.21	2.54	5.89
EL8	2.51	4.59	7.00
EL9	2.36	3.74	6.33
EL10	2.57	2.63	5.44
EL11	2.68	2.56	5.56
EL12	2.89	3.24	5.78
EL13	2.74	3.85	5.78
EL14	2.58	2.83	5.67
EL15	2.68	2.87	6.02
EL16	3.06	2.83	5.67
EL17	2.22	2.85	6.67
EL18	3.06	3.11	5.44
Risk factors weights	**0.65**	**0.23**	**0.12**
Dust, gas and other combustible materials – Explosion, ventilation, mine fire			
EX1	3.90	4.70	7.00
EX2	3.60	4.25	7.00
EX3	3.50	3.55	6.20
EX4	3.45	4.55	6.70

EX5	4.05	5.37	6.80
EX6	3.30	5.15	6.70
EX7	3.85	4.55	6.90
EX8	2.75	4.95	7.40
EX9	4.25	5.07	6.80
EX10	3.95	6.03	7.60
EX11	4.15	3.78	6.30
EX12	3.65	4.65	7.60
EX13	3.75	3.75	7.10
EX14	3.40	4.55	6.30
EX15	4.00	4.70	7.10
EX16	3.56	4.57	7.00
EX17	3.75	2.98	6.00
EX18	3.90	3.17	6.50
EX19	4.05	3.57	6.70
EX20	3.65	4.37	6.80
EX21	3.02	3.98	6.30
EX22	3.72	4.45	6.60
EX23	3.86	4.62	6.70
EX24	3.95	2.85	6.00
EX25	3.50	2.97	6.50
EX26	3.21	4.53	6.70
EX27	3.50	2.68	6.00
EX28	4.05	3.67	6.50
EX29	3.45	2.87	6.80
EX30	3.80	3.02	5.60
EX31	4.00	3.35	5.80
EX32	4.15	4.08	6.20
EX33	4.10	3.63	6.50
EX34	4.15	3.65	6.20
EX35	3.21	3.02	6.50
EX36	4.10	4.45	6.00
EX37	3.50	4.97	7.20
EX38	3.75	5.60	7.30
EX39	3.95	5.82	6.90
EX40	3.55	3.98	6.10
EX41	3.90	5.17	6.40
EX42	3.60	4.45	6.90
EX43	3.70	4.95	7.00
EX44	3.90	4.33	6.00
Risk factors weights	**0.14**	**0.66**	**0.20**
Other causes – Inundation, Unclassified			
OC1	3.78	4.22	6.67
OC2	3.17	2.93	6.00

OC3	3.78	5.00	7.78
OC4	4.00	4.39	7.00
OC5	3.44	2.52	6.11
OC6	3.34	2.78	5.89
OC7	3.89	2.61	5.57
OC8	3.39	3.50	5.91
OC9	3.67	2.96	6.44
OC10	3.39	4.26	6.89
OC11	4.50	4.85	5.67
OC12	3.72	3.72	5.67
OC13	4.11	4.91	7.78
OC14	3.89	4.31	6.46
OC15	2.19	2.74	6.33
OC16	2.56	4.93	7.11
OC17	3.28	4.15	5.80
OC18	3.90	4.83	6.00
Risk factors weights	**0.13**	**0.66**	**0.21**

Table D4. Defuzzified experts' opinion collected from the mine-4

Hazard number	C	E	P
Ground movement – Roof and side fall			
GM1	3.92	3.00	7.75
GM2	3.67	7.33	6.17
GM3	3.58	7.00	8.50
GM4	1.94	2.97	6.83
GM5	3.67	7.00	6.00
GM6	2.50	2.69	5.83
GM7	2.43	3.19	5.83
GM8	3.67	3.31	6.17
GM9	2.50	3.56	7.33
GM10	2.43	3.22	6.33
GM11	3.18	2.56	5.00
GM12	1.81	2.97	5.53
GM13	4.17	6.67	7.83
GM14	2.78	4.72	6.50
GM15	3.92	7.25	7.67
GM16	2.67	4.39	6.17
GM17	2.04	2.89	5.53
Risk factors weights	**0.21**	**0.67**	**0.12**
Transport machinery (non-winding) - Rope haulage and conveyor			
TM1	2.02	3.09	7.45
TM2	1.71	2.03	6.73
TM3	1.42	2.12	7.27
TM4	2.17	2.06	7.09
TM5	3.00	3.73	6.55
TM6	2.59	2.03	6.18
TM7	1.50	2.55	7.09
TM8	1.88	4.61	7.64
TM9	1.50	2.91	6.73
TM10	1.50	2.39	6.39
TM11	3.00	2.21	5.30
TM12	2.91	2.39	7.09
TM13	1.91	2.58	7.27
TM14	3.91	4.30	7.64
TM15	1.80	3.64	6.18
TM16	1.86	5.85	5.82
TM17	2.83	4.25	7.53
TM18	2.03	2.94	6.33
TM19	2.43	2.97	7.17
TM20	2.33	3.36	7.67
TM21	1.43	2.67	6.50
TM22	2.83	3.44	6.17

TM23	2.83	3.25	5.33
TM24	2.28	2.44	4.83
TM25	1.72	3.08	5.83
TM26	1.78	2.31	4.83
TM27	3.67	5.86	5.67
TM28	2.50	2.33	5.17
TM29	2.51	2.58	5.33
TM30	2.83	3.22	7.00
TM31	2.58	3.44	6.67
TM32	2.04	3.61	6.33
TM33	1.93	2.97	7.00
TM34	2.35	3.19	5.00
TM35	2.50	2.81	7.17
TM36	2.14	2.53	5.83
Risk factors weights	**0.59**	**0.24**	**0.17**
Machinery other than transport machinery - SDL, Haulage engine			
MM1	2.91	3.42	5.82
MM2	1.86	3.36	6.91
MM3	2.64	2.39	5.64
MM4	2.55	2.64	5.82
MM5	3.27	2.39	5.27
MM6	4.18	2.15	5.64
MM7	1.97	2.18	5.82
MM8	3.00	2.64	6.55
MM9	3.27	3.03	5.64
MM10	2.11	2.64	6.00
MM11	2.73	2.15	4.97
MM12	2.55	1.91	5.30
MM13	2.83	3.12	6.55
MM14	1.94	2.48	5.33
MM15	1.74	2.42	6.73
MM16	2.64	2.45	4.64
MM17	2.64	2.55	5.12
MM18	2.21	2.15	4.94
MM19	3.18	3.76	7.45
MM20	2.56	2.55	5.82
MM21	4.09	2.12	4.61
MM22	2.91	2.67	6.18
MM23	3.30	4.27	6.60
MM24	2.50	5.03	9.00
MM25	2.42	4.67	7.00
MM26	3.70	5.23	7.40
MM27	3.30	3.90	6.80
MM28	3.20	2.23	6.03

MM29	3.00	2.87	4.83
MM30	2.90	2.73	4.80
Risk factors weights	**0.69**	**0.22**	**0.09**
Explosives - Shot firing and blasting			
SF1	3.83	2.53	4.69
SF2	2.83	2.97	4.67
SF3	3.25	2.25	5.17
SF4	3.33	3.33	6.50
SF5	3.67	3.22	6.00
SF6	2.92	3.97	6.83
SF7	3.42	2.42	5.67
SF8	2.28	2.86	5.50
SF9	2.46	3.14	5.50
SF10	3.25	2.97	5.83
SF11	3.42	2.75	5.00
SF12	3.92	3.53	6.17
SF13	3.75	3.33	5.50
SF14	3.83	3.50	6.17
Risk factors weights	**0.72**	**0.17**	**0.11**
Electricity			
EL1	3.10	3.20	7.00
EL2	2.90	2.83	7.00
EL3	3.90	3.50	7.00
EL4	2.40	2.40	6.40
EL5	2.80	4.07	7.00
EL6	2.60	2.77	5.40
EL7	1.85	2.23	6.20
EL8	1.93	3.10	6.60
EL9	1.70	2.33	5.00
EL10	2.60	2.27	4.80
EL11	2.60	2.53	5.60
EL12	2.70	3.33	6.20
EL13	2.42	3.33	7.20
EL14	2.03	2.27	6.80
EL15	2.80	1.97	4.23
EL16	2.07	1.83	5.03
EL17	2.50	2.70	7.40
EL18	2.90	2.60	4.63
Risk factors weights	**0.70**	**0.09**	**0.21**
Dust, gas and other combustible materials – Explosion, ventilation, mine fire			
EX1	4.00	3.70	7.27
EX2	3.56	2.82	6.55
EX3	4.27	3.73	7.27
EX4	3.55	4.33	8.00

EX5	3.92	5.03	8.00
EX6	4.00	3.39	5.64
EX7	3.18	3.21	6.18
EX8	2.83	2.97	6.36
EX9	3.73	4.61	7.82
EX10	3.38	4.33	8.00
EX11	3.91	3.70	6.39
EX12	4.36	3.67	7.09
EX13	4.09	2.73	7.27
EX14	2.92	3.91	6.73
EX15	4.18	5.30	7.27
EX16	3.64	4.18	7.64
EX17	4.36	2.70	6.18
EX18	4.45	3.52	6.73
EX19	4.18	3.45	6.73
EX20	4.00	3.58	6.55
EX21	2.82	5.18	6.55
EX22	3.02	3.76	6.36
EX23	4.00	4.39	7.27
EX24	3.82	2.12	4.91
EX25	3.18	2.52	6.73
EX26	3.09	4.73	6.18
EX27	4.09	3.09	6.00
EX28	4.27	3.03	6.00
EX29	3.55	2.18	6.91
EX30	3.91	2.18	4.39
EX31	3.82	2.45	6.36
EX32	4.20	2.94	6.18
EX33	3.82	4.24	6.36
EX34	4.27	4.55	6.73
EX35	2.65	2.55	6.00
EX36	4.18	5.30	6.55
EX37	3.73	4.33	7.27
EX38	3.64	5.33	7.45
EX39	4.18	5.67	8.18
EX40	3.73	2.52	5.64
EX41	4.00	5.03	6.91
EX42	3.45	3.97	6.18
EX43	4.09	3.85	7.45
EX44	4.00	5.09	7.82
Risk factors weights	**0.63**	**0.26**	**0.11**
Other causes – Inundation, Unclassified			
OC1	4.20	3.40	7.20
OC2	2.80	2.00	5.03

OC3	3.90	4.80	7.40
OC4	4.10	4.07	8.40
OC5	3.50	2.40	6.40
OC6	2.13	2.13	5.80
OC7	4.00	2.13	5.40
OC8	3.02	2.40	4.83
OC9	3.70	2.10	7.00
OC10	3.90	3.20	7.40
OC11	4.30	3.60	4.80
OC12	4.00	2.57	5.20
OC13	4.20	4.47	7.60
OC14	3.40	3.57	7.00
OC15	2.62	2.73	6.60
OC16	2.60	3.80	7.00
OC17	3.10	2.63	4.83
OC18	3.67	4.67	5.33
Risk factors weights	**0.26**	**0.56**	**0.18**

Table D5. Defuzzified experts' opinion collected from the mine-5

Hazard number	C	E	P
Ground movement – Roof and side fall			
GM1	3.83	3.26	7.33
GM2	3.28	6.22	6.33
GM3	3.22	6.78	7.89
GM4	2.41	4.44	6.89
GM5	3.33	6.67	7.00
GM6	2.62	3.94	6.11
GM7	2.83	4.07	6.56
GM8	3.56	4.54	7.00
GM9	2.56	4.24	6.89
GM10	2.72	3.74	6.89
GM11	3.39	3.13	5.78
GM12	2.15	4.17	5.78
GM13	3.83	6.22	7.22
GM14	2.84	5.17	7.11
GM15	3.89	7.24	8.11
GM16	2.89	5.13	6.11
GM17	2.17	3.30	5.46
Risk factors weights	**0.15**	**0.61**	**0.24**
Transport machinery (non-winding) - Rope haulage and conveyor			
TM1	2.36	4.14	6.57
TM2	2.25	3.05	6.67
TM3	1.98	2.76	6.86
TM4	2.31	3.14	6.76
TM5	3.48	3.76	7.24
TM6	3.39	3.02	6.19
TM7	2.17	3.81	6.57
TM8	2.44	4.78	7.14
TM9	2.30	4.19	7.14
TM10	2.20	3.62	6.29
TM11	2.76	2.44	5.71
TM12	3.38	2.92	6.29
TM13	2.12	4.21	6.76
TM14	4.05	5.38	6.00
TM15	2.36	4.10	7.33
TM16	2.44	5.70	6.48
TM17	2.94	3.78	6.44
TM18	2.29	3.20	6.44
TM19	2.34	3.44	7.33
TM20	2.06	3.39	7.00
TM21	1.88	2.43	6.22
TM22	2.72	3.19	6.44

TM23	2.45	3.19	6.00
TM24	2.25	2.20	5.24
TM25	2.49	3.52	5.44
TM26	1.91	3.02	5.67
TM27	3.44	5.06	5.67
TM28	2.68	2.61	5.00
TM29	2.89	3.19	5.78
TM30	2.68	3.44	6.22
TM31	2.62	4.13	6.33
TM32	1.90	3.69	6.11
TM33	1.50	2.83	6.33
TM34	2.30	3.74	6.00
TM35	2.67	3.22	6.44
TM36	2.73	3.87	5.57
Risk factors weights	**0.66**	**0.10**	**0.24**
Machinery other than transport machinery - SDL, Haulage engine			
MM1	2.63	3.70	6.90
MM2	2.40	3.90	7.20
MM3	2.95	3.02	6.20
MM4	2.75	3.05	6.30
MM5	3.15	2.98	5.80
MM6	3.70	3.43	5.80
MM7	2.18	3.42	7.10
MM8	3.20	3.78	6.40
MM9	3.45	3.82	6.00
MM10	2.51	3.88	6.50
MM11	2.61	2.52	6.20
MM12	2.32	2.42	6.10
MM13	2.36	3.32	7.10
MM14	2.33	3.42	6.20
MM15	2.10	4.35	7.30
MM16	2.75	3.60	5.52
MM17	3.05	2.73	5.50
MM18	2.37	2.75	5.70
MM19	3.25	3.97	7.10
MM20	3.05	3.50	6.50
MM21	3.85	2.70	5.20
MM22	3.15	2.90	6.70
MM23	3.10	5.15	5.70
MM24	2.75	5.50	6.80
MM25	2.78	4.87	6.40
MM26	3.90	5.32	6.40
MM27	3.80	4.37	5.90
MM28	2.95	2.67	5.60

MM29	3.10	3.38	5.30
MM30	3.12	2.02	4.42
Risk factors weights	**0.65**	**0.15**	**0.20**
Explosives - Shot firing and blasting			
SF1	3.71	2.74	5.00
SF2	3.14	3.24	5.29
SF3	3.71	2.98	5.57
SF4	3.57	3.19	5.71
SF5	3.43	2.24	5.31
SF6	2.87	3.29	6.43
SF7	3.71	2.43	5.86
SF8	2.61	2.50	6.29
SF9	3.07	2.50	6.00
SF10	2.86	3.21	5.86
SF11	3.64	3.19	5.14
SF12	3.86	3.26	5.71
SF13	3.21	2.64	4.74
SF14	3.36	3.10	5.14
Risk factors weights	**0.70**	**0.20**	**0.10**
Electricity			
EL1	2.63	3.09	5.79
EL2	2.84	3.05	6.53
EL3	3.21	3.61	6.00
EL4	2.33	2.98	5.79
EL5	2.58	3.77	6.11
EL6	2.64	2.72	6.21
EL7	2.10	3.14	6.00
EL8	2.13	3.47	6.21
EL9	1.99	3.30	5.58
EL10	2.48	2.49	5.37
EL11	2.69	2.44	6.11
EL12	3.00	3.30	5.58
EL13	2.54	2.70	6.53
EL14	2.47	2.26	6.74
EL15	2.79	2.75	5.49
EL16	2.44	2.75	5.58
EL17	2.26	2.70	6.53
EL18	2.43	2.86	6.21
Risk factors weights	**0.73**	**0.10**	**0.17**
Dust, gas and other combustible materials – Explosion, ventilation, mine fire			
EX1	4.36	4.65	7.18
EX2	3.86	4.77	7.36
EX3	3.91	3.26	6.73
EX4	3.23	4.98	7.45

EX5	3.86	4.92	7.27
EX6	4.05	5.95	6.91
EX7	3.59	4.47	6.82
EX8	3.23	4.70	7.00
EX9	4.05	4.91	7.45
EX10	4.00	5.94	7.82
EX11	4.14	4.45	6.55
EX12	4.36	4.65	7.27
EX13	3.91	3.45	7.18
EX14	3.68	5.17	7.27
EX15	4.00	4.29	7.36
EX16	3.55	4.89	7.73
EX17	3.36	3.56	5.82
EX18	3.73	2.89	5.64
EX19	4.18	3.62	5.45
EX20	3.55	4.29	5.73
EX21	2.83	4.59	6.18
EX22	3.23	4.48	6.27
EX23	3.82	4.50	6.45
EX24	3.50	2.65	5.55
EX25	3.23	2.85	7.00
EX26	3.32	4.86	6.18
EX27	3.45	2.89	6.45
EX28	3.77	3.65	5.91
EX29	3.59	3.05	5.73
EX30	3.86	2.98	5.36
EX31	3.41	3.06	5.82
EX32	4.05	4.05	6.55
EX33	3.45	3.67	6.27
EX34	4.05	4.06	5.82
EX35	3.09	3.15	5.64
EX36	4.05	4.98	6.18
EX37	3.55	4.65	6.64
EX38	3.55	5.50	6.91
EX39	4.32	5.55	7.82
EX40	3.91	4.17	5.64
EX41	3.68	5.18	6.73
EX42	3.55	4.62	6.73
EX43	3.86	4.80	6.45
EX44	3.95	4.95	6.27
Risk factors weights	**0.64**	**0.25**	**0.11**
Other causes – Inundation, Unclassified			
OC1	3.32	3.96	6.84
OC2	2.54	2.25	5.39

OC3	3.43	4.88	7.68
OC4	3.58	4.07	7.68
OC5	3.47	2.72	6.42
OC6	2.76	3.18	6.53
OC7	3.68	2.60	5.58
OC8	3.17	3.98	5.70
OC9	3.27	2.32	6.42
OC10	3.22	4.09	7.05
OC11	4.16	4.26	5.16
OC12	3.37	3.37	5.26
OC13	4.37	4.98	7.37
OC14	3.26	3.33	6.32
OC15	2.18	2.56	6.74
OC16	2.84	4.68	7.89
OC17	3.32	3.25	5.35
OC18	3.33	4.74	5.78
Risk factors weights	**0.67**	**0.22**	**0.11**

Table D6. Defuzzified experts' opinion collected from the mine-6

Hazard number	C	E	P
Ground movement – Roof and side fall			
GM1	3.57	3.79	7.14
GM2	3.10	5.71	6.19
GM3	3.24	5.92	6.95
GM4	2.33	4.30	6.38
GM5	3.29	5.67	5.90
GM6	2.45	4.13	5.24
GM7	2.31	4.51	6.29
GM8	3.10	4.19	5.62
GM9	2.67	3.59	6.67
GM10	2.58	3.52	6.38
GM11	3.24	4.40	5.62
GM12	1.84	3.75	5.83
GM13	3.48	5.71	6.95
GM14	2.44	5.25	7.05
GM15	3.86	7.05	7.05
GM16	2.82	5.43	6.48
GM17	2.51	4.05	5.65
Risk factors weights	**0.14**	**0.62**	**0.24**
Transport machinery (non-winding) - Rope haulage and conveyor			
TM1	1.94	4.19	6.33
TM2	2.23	3.31	6.33
TM3	1.76	2.57	6.00
TM4	2.46	3.11	6.56
TM5	3.39	3.80	7.00
TM6	2.89	3.35	6.22
TM7	1.94	3.59	6.33
TM8	2.36	4.63	6.89
TM9	2.31	4.48	6.56
TM10	2.09	3.52	6.78
TM11	2.83	2.54	5.78
TM12	3.33	3.13	6.78
TM13	1.79	4.02	6.00
TM14	3.89	5.19	6.00
TM15	2.35	4.31	6.78
TM16	2.62	6.50	6.22
TM17	2.68	4.31	6.11
TM18	2.16	3.33	6.11
TM19	2.19	3.41	6.00
TM20	2.19	3.89	6.78
TM21	1.70	1.89	5.89
TM22	2.56	3.04	6.44

TM23	2.44	4.17	5.56
TM24	2.44	2.50	5.24
TM25	2.56	3.78	5.46
TM26	1.78	3.70	5.78
TM27	3.78	5.44	5.89
TM28	2.54	2.81	5.22
TM29	2.74	3.35	5.67
TM30	2.56	3.67	6.44
TM31	2.22	3.70	6.33
TM32	1.98	3.94	5.78
TM33	1.68	2.76	6.11
TM34	2.22	4.39	5.11
TM35	2.62	3.44	6.22
TM36	2.80	3.63	5.78
Risk factors weights	**0.71**	**0.09**	**0.20**
Machinery other than transport machinery - SDL, Haulage engine			
MM1	2.72	3.35	6.12
MM2	2.33	3.49	6.59
MM3	2.82	2.39	5.53
MM4	2.50	2.73	5.76
MM5	3.29	2.55	5.29
MM6	3.82	2.98	5.76
MM7	2.34	3.16	6.24
MM8	3.47	2.94	6.12
MM9	3.59	3.47	5.18
MM10	2.26	3.94	6.12
MM11	2.60	2.47	5.33
MM12	2.43	2.20	5.88
MM13	2.27	3.59	6.59
MM14	2.31	3.18	5.76
MM15	2.23	3.55	7.31
MM16	3.12	3.35	5.29
MM17	3.01	2.78	5.29
MM18	2.46	3.27	5.78
MM19	3.53	4.16	6.82
MM20	3.41	3.06	5.65
MM21	3.88	2.65	5.18
MM22	3.41	3.14	6.12
MM23	3.22	4.95	6.32
MM24	2.59	5.18	7.16
MM25	3.11	4.96	6.42
MM26	3.68	4.21	6.11
MM27	3.47	3.56	6.00
MM28	3.21	3.33	6.00

MM29	3.37	3.14	5.16
MM30	3.32	2.39	4.65
Risk factors weights	**0.09**	**0.69**	**0.22**
Explosives - Shot firing and blasting			
SF1	3.83	3.39	5.78
SF2	3.17	3.17	5.44
SF3	3.56	3.59	5.56
SF4	3.56	3.41	6.22
SF5	3.61	3.07	5.44
SF6	3.01	3.43	6.33
SF7	3.39	3.06	6.00
SF8	2.84	2.37	5.33
SF9	2.75	2.69	6.22
SF10	2.73	3.48	5.67
SF11	3.61	3.17	5.13
SF12	3.83	3.63	6.02
SF13	3.50	3.46	5.57
SF14	3.51	4.07	5.67
Risk factors weights	**0.70**	**0.08**	**0.22**
Electricity			
EL1	2.85	3.32	5.90
EL2	2.75	2.63	5.40
EL3	3.35	3.92	6.20
EL4	2.70	2.78	5.50
EL5	2.52	4.33	6.20
EL6	2.67	3.37	5.50
EL7	2.20	3.08	5.90
EL8	2.32	3.93	5.80
EL9	2.33	3.52	6.20
EL10	2.28	2.90	5.50
EL11	2.51	2.68	5.30
EL12	3.00	3.52	6.00
EL13	3.15	3.37	6.40
EL14	2.51	2.28	5.90
EL15	3.26	2.95	5.40
EL16	3.07	3.05	5.50
EL17	2.23	3.55	6.70
EL18	2.85	3.80	5.20
Risk factors weights	**0.66**	**0.22**	**0.12**
Dust, gas and other combustible materials – Explosion, ventilation, mine fire			
EX1	4.00	4.06	6.25
EX2	3.88	4.50	6.38
EX3	3.31	3.33	6.25
EX4	3.50	4.46	6.75

EX5	3.81	5.17	6.88
EX6	3.69	4.54	7.00
EX7	4.19	4.52	6.25
EX8	3.50	4.08	7.88
EX9	4.06	4.83	6.50
EX10	3.69	5.42	7.75
EX11	3.69	3.79	5.63
EX12	4.19	4.58	6.75
EX13	3.75	3.54	6.13
EX14	3.38	4.42	6.13
EX15	3.88	4.46	7.13
EX16	3.63	4.94	5.75
EX17	3.56	3.02	6.13
EX18	3.45	2.38	6.13
EX19	3.94	3.23	5.88
EX20	3.69	4.96	6.13
EX21	2.51	4.04	6.25
EX22	3.02	3.02	6.13
EX23	3.88	4.40	6.63
EX24	3.31	2.56	5.75
EX25	3.70	3.08	6.75
EX26	2.89	3.96	7.00
EX27	3.81	3.08	5.88
EX28	3.69	3.46	6.38
EX29	3.31	2.35	6.50
EX30	4.06	2.92	5.38
EX31	3.63	2.85	6.00
EX32	4.06	3.77	6.13
EX33	3.94	4.44	6.38
EX34	3.88	3.69	6.25
EX35	3.07	3.40	6.38
EX36	4.06	4.85	5.90
EX37	3.38	4.90	6.52
EX38	3.75	5.29	7.25
EX39	4.19	5.54	6.75
EX40	4.00	4.67	5.50
EX41	3.69	5.65	6.63
EX42	4.06	5.21	6.25
EX43	3.69	5.10	6.63
EX44	3.75	4.65	6.75
Risk factors weights	**0.62**	**0.11**	**0.27**
Other causes – Inundation, Unclassified			
OC1	3.48	4.56	6.95
OC2	2.90	2.37	5.05

OC3	3.57	5.33	7.81
OC4	3.62	3.98	7.33
OC5	3.48	2.95	6.10
OC6	2.99	3.27	5.71
OC7	3.90	2.83	5.17
OC8	2.71	3.65	5.46
OC9	3.33	2.29	6.19
OC10	3.52	4.32	7.52
OC11	4.43	4.57	5.52
OC12	3.62	3.19	5.52
OC13	3.86	4.54	7.33
OC14	4.00	4.14	6.00
OC15	1.83	2.46	6.76
OC16	2.86	5.33	7.71
OC17	3.36	4.03	5.90
OC18	3.75	4.86	5.50
Risk factors weights	**0.13**	**0.64**	**0.23**

APPENDIX E: Average Pairwise Comparison Data Collected from the Mines

Table E1. Average pairwise comparison data collected from the mine-1

	Ground movement (fall of roof/ side)	Transport machinery (rope haulage, conveyor)	Machinery other than transport machinery	Explosives (shot firing and blasting)	Electricity	Dust, gas and other combustible materials	Other causes (inundation)
Ground movement (fall of roof/ side)	1.00	3.50	4.00	3.83	5.33	1.45	5.38
Transport machinery (rope haulage, conveyor)	0.29	1.00	1.75	2.01	4.17	1.81	1.65
Machinery other than transport machinery	0.25	0.57	1.00	1.81	1.83	1.27	1.28
Explosives (shot firing and blasting)	0.26	0.50	0.55	1.00	2.58	1.68	2.26
Electricity	0.19	0.24	0.55	0.39	1.00	0.46	0.93
Dust, gas and other combustible materials	0.69	0.55	0.79	0.59	2.16	1.00	4.33
Other causes (inundation)	0.19	0.61	0.78	0.44	1.07	0.23	1.00

Table E2. Average pairwise comparison data collected from the mine-2

	Ground movement (fall of roof/ side)	Transport machinery (rope haulage, conveyor)	Machinery other than transport machinery	Explosives (shot firing and blasting)	Electricity	Dust, gas and other combustible materials	Other causes (inundation)
Ground movement (fall of roof/ side)	1.00	1.71	3.14	3.93	3.86	2.36	3.90
Transport machinery (rope haulage, conveyor)	0.58	1.00	2.00	2.74	3.86	2.98	4.08
Machinery other than transport machinery	0.32	0.50	1.00	1.54	1.56	0.98	2.64
Explosives (shot firing and blasting)	0.25	0.36	0.65	1.00	1.90	2.54	3.02
Electricity	0.26	0.26	0.64	0.53	1.00	2.04	2.65
Dust, gas and other combustible materials	0.42	0.34	1.02	0.39	0.49	1.00	2.43
Other causes (inundation)	0.26	0.25	0.38	0.33	0.38	0.41	1.00

Table E3. Average pairwise comparison data collected from the mine-3

	Ground movement (fall of roof/ side)	Transport machinery (rope haulage, conveyor)	Machinery other than transport machinery	Explosives (shot firing and blasting)	Electricity	dust, gas and other combustible materials	Other causes (inundation)
Ground movement (fall of roof/ side)	1.00	3.00	3.44	4.00	5.44	5.22	6.11
Transport machinery (rope haulage, conveyor)	0.33	1.00	1.72	2.98	4.11	3.68	4.44
Machinery other than transport machinery	0.29	0.58	1.00	2.37	3.44	3.13	2.89
Explosives (shot firing and blasting)	0.25	0.34	0.42	1.00	4.11	2.83	2.78
Electricity	0.18	0.24	0.29	0.24	1.00	1.42	1.65
Dust, gas and other combustible materials	0.19	0.27	0.32	0.35	0.71	1.00	2.15
Other causes (inundation)	0.16	0.23	0.35	0.36	0.61	0.47	1.00

Table E4. Average pairwise comparison data collected from the mine-4

	Ground movement (fall of roof/ side)	Transport machinery (rope haulage, conveyor)	Machinery other than transport machinery	Explosives (shot firing and blasting)	Electricity	dust, gas and other combustible materials	Other causes (inundation)
Ground movement (fall of roof/ side)	1.00	1.86	3.00	3.50	6.57	1.98	3.00
Transport machinery (rope haulage, conveyor)	0.54	1.00	2.71	3.50	5.00	2.16	3.05
Machinery other than transport machinery	0.33	0.37	1.00	2.21	3.43	1.62	3.32
Explosives (shot firing and blasting)	0.29	0.29	0.45	1.00	2.00	1.06	1.87
Electricity	0.15	0.20	0.29	0.50	1.00	0.49	1.85
Dust, gas and other combustible materials	0.51	0.46	0.62	0.94	2.04	1.00	2.57
Other causes (inundation)	0.33	0.33	0.30	0.53	0.54	0.39	1.00

Table E5. Average pairwise comparison data collected from the mine-5

	Ground movement (fall of roof/ side)	Transport machinery (rope haulage, conveyor)	Machinery other than transport machinery	Explosives (shot firing and blasting)	Electricity	dust, gas and other combustible materials	Other causes (inundation)
Ground movement (fall of roof/ side)	1.00	3.83	5.00	6.33	5.67	2.97	4.06
Transport machinery (rope haulage, conveyor)	0.26	1.00	2.00	3.83	2.83	1.11	3.62
Machinery other than transport machinery	0.20	0.50	1.00	1.83	1.83	0.90	1.73
Explosives (shot firing and blasting)	0.16	0.26	0.55	1.00	1.58	0.59	1.45
Electricity	0.18	0.35	0.55	0.63	1.00	0.41	1.16
Dust, gas and other combustible materials	0.34	0.90	1.12	1.69	2.43	1.00	2.25
Other causes (inundation)	0.25	0.28	0.58	0.69	0.86	0.44	1.00

Table E6. Average pairwise comparison data collected from the mine-6

	Ground movement (fall of roof/ side)	Transport machinery (rope haulage, conveyor)	Machinery other than transport machinery	Explosives (shot firing and blasting)	Electricity	dust, gas and other combustible materials	Other causes (inundation)
Ground movement (fall of roof/ side)	1.00	2.38	3.13	3.75	5.88	1.91	3.50
Transport machinery (rope haulage, conveyor)	0.42	1.00	2.00	3.29	5.25	1.70	2.56
Machinery other than transport machinery	0.32	0.50	1.00	1.88	3.38	1.75	2.69
Explosives (shot firing and blasting)	0.27	0.30	0.53	1.00	2.63	1.83	2.68
Electricity	0.17	0.19	0.30	0.38	1.00	0.43	0.81
Dust, gas and other combustible materials	0.52	0.59	0.57	0.55	2.31	1.00	2.69
Other causes (inundation)	0.29	0.39	0.37	0.37	1.23	0.37	1.00

LIST OF PUBLICATIONS

Internationally indexed journals

1. Ala, C. K., & Tripathy, D. P. (2016). Qualitative assessment of strata control in an Indian underground coal mine. *Journal of The Institution of Engineers (India): Series D*, *97*(1), 99–104. http://doi.org/10.1007/s40033-015-0082-8
2. Tripathy, D. P., & Ala, C. K. (2018). Identification of safety hazards in Indian underground coal mines. *Journal of Sustainable Mining*, *17*(4), 175–183. http://doi.org/10.1016/j.jsm.2018.07.005
3. Tripathy, D. P., & Ala, C. K. (2018). Risk assessment in underground coalmines using fuzzy logic in the presence of uncertainty. *Journal of The Institution of Engineers (India): Series D*, *99*(1), 157–163. http://doi.org/10.1007/s40033-018-0154-7

Other journals

1. Tripathy, D. P., & Ala, C. K. (2015). Investigation of equipment related fatal accidents in Indian coal mines. *Safety Equipment Review*, *16*(6), 14–19.

Conferences

1. Ala, C. K., & Tripathy, D. P. (2016). A novel methodology for risk assessment in underground coal mines. In *Proceedings of Risk and Resilience Mining Solutions* (pp. 91-116). Vancouver, Canada: InfoMine.