



An empirical study on the survivability of trapped miners in underground mines post-accident – a global analysis

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Abstract

A significant number of fatalities in the mining industry are a result of the entrapment of miners underground post-accident. These fatalities happen when miners survive the initial event of an accident, but remain trapped or lost underground in unknown and life-threatening locations for an extended period. Consequently, if not rescued as quickly as possible, the trapped miners may succumb to their injuries and/or the lack of essential and life-sustaining necessities such as fresh air, water, food and medication. Despite their severity, specific research pertaining to the analysis of incidents involving trapped miners and the survivability of trapped miners post-accident is limited. This can be partially attributed to the incorrect reporting and categorizing of these incidents according to the initial event, although miners may survive the initial event, but later succumb to the secondary effects of being trapped underground. However, in some cases, it may be difficult to determine if the miners died from the initial event or due to being trapped underground. The trapped miner incidents tend to be more complex and challenging than typical accidents due to the lack of reliable information regarding the precise locations and the health status of the trapped miners (whether they are severely injured, still alive or deceased) post-accident. Therefore, the aim of this study was to investigate and analyze incidents involving trapped miners and assess the survivability of the trapped miners post-accident. This was based on the consolidation of data collected from 39 incidents involving trapped miners globally between 2006 and 2024. The dataset was validated and cross-referenced using multiple sources including peer-reviewed journal articles, official investigation reports and reputable online news publications. The data was classified by commodity, mining method, cause or initial event, area of occurrence and depth of entrapment. From the analysis, the total number of trapped miners, $N = 1,324$; survivors, $S = 337$ (25.5%); and the resulting fatalities, $F = 972$ (73.4%), were determined. The search and rescue (SAR) duration was an average of 14.9 days while in some cases the trapped miners were never found. The survival probability of the trapped miners post-accident was analyzed using the Kaplan-Meier, Nelson-Aalen, and Life Table Estimator models. These models were used to analyze and visualize the survival probability of the trapped miners over the entrapment period.

Keywords Entrapment · Search and rescue (SAR) · Survival probability · And fatality rates

Introduction

Mining has always been an important driver of economic growth and civilization (i.e. industrialization, technology development, energy supply, source of employment, and infrastructure development). However, it is also ranked amongst the riskiest and most hazardous industries

globally. This can be attributed to the poor safety records due to the unacceptably high rates of accidents. Mining accidents often result in multiple fatalities, serious injuries, and long-term disabilities among the mine personnel. Some mining accidents can cause extensive and costly damages to infrastructure, property, and critical equipment. Additionally, some incidents can have significant impacts on the environment and surrounding communities. The major causes of accidents (e.g. rock falls, fires and explosions, and transportation and machinery) and their root causes (e.g. poor safety culture, violations, and human error) in the mining industry have been extensively researched globally (Quintero et al. 2024; Duarte et al. 2021; Zhang

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et al. 2020; Bonsu et al. 2017; Saleh and Cummings 2011; Ruff et al. 2011; Jacinto and Soares 2008; Komljenovic et al. 2008; Kecojevic et al. 2007; Cawley 2003; Blank et al. 1996; Mitchell et al. 1998).

Among the major causes of fatalities in underground mines, this study aims to demonstrate that a significant proportion are a consequence of the entrapment of miners underground. This happens when miners survive the initial event of an accident, but remain trapped or lost underground for an extended period without any help (Ngwenyama and Webber-Youngman 2023). If the trapped miners are not located and rescued as quickly as possible; they may succumb to their injuries, due to the lack of supply of essential and life-sustaining necessities such as fresh air, water, food and medication, or other health related issues. According to Lehnen (2016), entrapments in underground mines do not occur frequently, but are unpredictable and very complex when they do occur. This is a result of limited information about the exact number of trapped miners, their locations and whether they are seriously injured, still alive or deceased post-accident. The entrapment of miners necessitates the activation of search and rescue (SAR) operations to save survivors. This has been the most used and relied on method for attempting to locate and rescue trapped miners underground. However; it has proven ineffective, slow and risky (Molyneaux 2016; Sacks 1977). This is despite the SAR method being well researched for its efficiency and effectiveness for underground emergencies (Kowalski-Trakofler et al. 2010; Kowalski-Trakofler and Vaught 2012; Jansky et al. 2016). Without accurate locations of the trapped miners, rescuers

are forced to search for the trapped miners in presumed or random areas throughout the mine. These are areas where the trapped miners were seen last or where they were expected to be working or travelling at the time or just before the occurrence of the accident. This makes SAR operations tedious and time-consuming processes which in turn increases the risk of fatalities.

In addition to the unknown locations of the trapped miners, SAR operations can be delayed by the uncongenial post-accident conditions in the mine. According to Molyneaux (2016); the post-accident conditions underground can be extremely hazardous and are characterized by a combination of factors such as cave-ins and rubble, flooding, heavy smoke, dust, harmful gases, high humidity, poor illumination, scattered rails and collapsed beams, uneven surfaces, fallen steel supports, and exposed electrical cables (Fig. 1). Delays during SAR operations can have financial implications such as lost production time, rescue costs, and temporary and permanent closure of mines. For example, it took a multinational effort of up to US\$ 20 million to rescue 33 workers who were trapped underground for 69 days at the collapsed Chilean San Jose mine in 2010 (Jiménez-Martínez 2016).

According to a report by Mining Safety (2023), it is critical and a matter of urgency that miners affected by an accident are rendered emergency medical care to improve their chances of survival. This is supported by the Golden-hour concept (resuscitative-hour) which stipulates that critically injured persons have a survival chance if medical care is rendered within the first hour after an accident (Lerner and Moscati 2001; Bledsoe 2002). The Golden-72-hour concept



Fig. 1 Post-accident conditions in underground mines (Molyneaux 2016)

suggests that people can survive up to 72 h without food and water (Hakami et al. 2013). Adults who are unharmed in an accident, but with supply of fresh air and water, have a higher likelihood of survival, provided that they are recovered within 72 h (Huo et al. 2011). According to Huo et al. (2011), affected people have a better survival chance within 48 h, but it reduces exponentially beyond the 72-hour time period and survival becomes extremely less likely after 120 h. This highlights the critical need for efficient SAR operations to enhance the survival prospects of trapped miners.

Despite frequently making headlines, research pertaining to trapped miner incidents remains limited. This can be attributed to the fact that these incidents are often incorrectly reported and classified. Often, the initial event or origin of an accident is reported and classified as the cause of fatality, while it was actually due to the consequences of being trapped in unfavorable and life-threatening conditions underground. According to the International Organization for Standardization (2017), mining accidents should be classified by their origin or cause, the type of accident and by their result or consequence. As such, if a miner survives an accident, but is fatally injured after some time, then the cause of the fatality should be classified as “trapped underground”. Nonetheless, the trapped miner fatalities are subsequent to the initial events of accidents such as rock falls, fires and explosions, water inundation, air-blast, mud-rush, and poor visibility. This suggests a need for a standardized, detailed and consistent methodology for recording incidents where miners have become trapped underground. The current reports are vague, inconsistent and often do not include some critical information about the trapped miners.

Literature review

Entrapment of persons in other high-risk environments

Entrapments do not only happen in underground mines, but are also common in other high-risk industries and environments such as skyscrapers, construction, maritime, tunneling, and oil-and-gas. Similar to underground mines, these environments are comprised of confined spaces and hazardous conditions that can cause and increase the risk of entrapments. This section of the study explores the similarities and relatedness of these incidents to the trapped miner incidents in underground mines. In opencast mines, miners have occasionally become trapped as a result of events such as slope failure, bench collapse and landslides. For example, 53 miners were buried and trapped in a landslide at the Xinjing

opencast coal mine in China in February, 2023 (Wang et al. 2024). Another landslide incident occurred at the Turkish Copler open-pit gold mine leading to the burial and entrapment of 9 miners in February 2024 (Büyükkapınar et al. 2025). These trapped miner incidents can be related to the entrapment of people in the rubble of collapsed buildings due to natural disasters such as earthquakes (Fig. 2) (Reinoso et al. 2018). During such disasters, the survivors may experience life-threatening conditions such as suffocation, severe hemorrhage, crush syndrome, dehydration, and heat exhaustion (Akın et al. 2024). These conditions necessitate urgent and well-coordinated emergency SAR operations to improve the survival chances of the trapped people (El-Tawil and Aguirre 2010).

In communities and urban areas, a number of people have been reported to have died from being trapped in debris of collapsed constructions sites (Xie et al. 2023; Zhang et al. 2018a; Wei et al. 2017; Zade and Badnerkar 2011; Huo et al. 2011; Todokoro 2009; Chen et al. 2000). In 2023, an earthquake affected a total of 662 people and killed 131 people, while the 530 survivors became trapped under rubble for a week in Turkey (Sarı et al. 2023). Another major earthquake occurred in Lushan in 2013, resulting in 200 deaths and more than 12,000 injuries (Duan et al. 2022; Tang et al. 2017). Many other earthquake disasters that resulted in entrapments were investigated by Rom and Kelman (2020). In these situations, the trapped people die from a lack of medical aid. Similar to underground accidents, people may survive the initial collapse of the building, but remain trapped for a longer period (Macintyre et al. 2011). A number of studies have focused on the time-to-rescue for the trapped people in order to stand a chance of saving lives. SAR in collapsed buildings can last between 24 and 48 h (Pegel et al. 2018). It may be difficult for the trapped people to survive beyond the fourth day (Epstein et al. 2023). Survivors would normally be found within voids formed from the collapsing structure (Hu et al. 2019). However, the estimation of casualty can be linked to the extent of damage of the buildings (Spence and So 2009). During an emergency, the size or number of rescue teams and their readiness or preparedness play a critical role in determining the outcome of entrapments. This requires modelling of the critical rescue logistics based on historical survival rates. The survival rate among trapped persons can be improved with the availability of a sufficient number of well-equipped and rapidly deployable rescue teams. This shows the importance of strategic planning and resource allocation in emergency response. Such insights can be applied to mine emergencies and SAR processes for trapped miners.

Flooding has also been identified as a major contributor to the entrapment of people (Gupta et al. 2012). Coastal drowning has resulted in people being trapped at sea and



Fig. 2 People trapped in rubble from collapsed buildings due to an earthquake (Reinoso et al. 2018)

oceans (Webber et al. 2020; Pereiro et al. 2021). In the year 2018; about 237 people were reported trapped due to 176 water traffic accidents in China (Wang et al. 2021). Inland, thousands of trapped persons who were hiking, hunting and performing other adventurous activities in wilderness areas, mountains, forests, jungles and national parks have been reported (Hashimoto et al. 2022; Koester 2018; Drexel et al. 2018; Sava et al. 2016; Li and Dong 2014; Doherty et al. 2014; Doke 2012). Other trapped people who needed SAR

operations have been reported in deserts (Almujalli and Altuwaijri 2023a, b).

Accident analysis models

This section evaluates the applicability of existing accident analysis models to the trapped miner incidents and their ability to account and estimate the survivability of trapped miners post-accident. The commonly used accident analysis

models include the Swiss Cheese Model (SCM), Analytic Hierarchy Process (AHP), Event and Causal Factors (ECF), “2–4 or 24” model, AcciMap Model, Structural Equation Model (SEM), Accident Causation Tree (ACT), Human Factors Analysis and Classification System (HFACS), Cause-Consequence Analysis (CCA), Management Oversight and Risk Tree (MORT), System Theoretic Accident Modeling and Process Model (STAMP) and the Feyer and Williamson method. The HFACS and AHP are amongst the commonly used models in the mining industry while the STAMP model has also been employed (Zhang et al. 2024; Düzgün and Leveson 2018; Liu et al. 2018; Qiao et al. 2019). The HFACS is a system-based model, developed from the principles of the SCM. It provides an analysis framework that investigates human errors and unsafe acts, and their consequences (Shappell and Wiegmann 2000). These investigations often attribute the causes to factors such as operator error, negligence or lack of competency. Yang et al. (2022) provides an improved HFACS model which incorporates external factors.

The HFACS and STAMP models are versatile as they have also been extensively used in the analysis of road traffic accidents (Dong et al. 2024). Similarly, the SCM and the Feyer and Williamson models focus on causal factors or chain of causes that lead to an accident such as human error, systemic factors and their relationship (Sanmiquel-Pera et al. 2019). These models can be used to systematically identify active and latent failures within organizations. Salmon et al. (2012) conducted a comparison of the AcciMap, HFACS and STAMP while Igdene and Johnson (2020) conducted a similar comparison but also including the ECF model. The HFACS has also been compared to the “2–4” model (Fu et al. 2017). Although mine accidents and their root causes have been extensively studied, there is a significant lack of studies that specifically and systematically analyze the post-accident survivability of trapped miners. Most of the existing models focus on hazard identification, causal analysis, prevention strategies, and safety management systems, but

do not systematically assess factors such as post-accident survivability of trapped miners. The applicability of the different accident analysis models is summarized in Table 1.

These models have a limited potential for analyzing post-accident survivability of trapped miners. As such, risk assessment tools such as the Bowtie and Fault Tree analysis were also considered for their applicability. The advantage of these tools is that they incorporate a systemic interaction of people, the environment and safety systems to provide a comprehensive evaluation of a risk (Zhang et al. 2018b). For example, the Bowtie risk assessment was applied in Fig. 3 to represent the relationship between hazards, potential consequences, and controls to prevent trapped miner accidents and fatalities.

This tool allows the identification of the top event, its possible causes and control measures, and consequences and mitigation measures. This can help with understanding the failure path and adequate controls when miners have become trapped underground. In a Bowtie risk assessment, the top event or risk is the entrapment of a miner.

Survival probability estimation of trapped miners

This study focuses on the point just after the occurrence of an accident to the point of rescue (time-to-rescue) and the survival chances of the trapped miners. The study assumes that an accident has occurred and that there is an urgent need to rescue the trapped miners. However, there are limited studies that analyze the survivability of trapped miners in the mining industry. In other sectors, various models have been developed to estimate the survival probability of patients following traumatic incidents such as vehicle collisions, falls from height, armed conflicts, and pedestrian accidents (Norouzi et al. 2013; Huabangyang et al. 2021). According to Davie et al. (2021), about 70% of deaths from traumatic accidents happen before the patients reach the hospitals. Even those who reach the hospital alive may eventually succumb to their injuries (Hansen et al. 2020).

Table 1 Use of accident analysis models in the mining industry

Accident analysis model	Applicability to mine accident analysis	Focus on human factors	System complexity, adaptability and flexibility	Potential use for post-accident survivability analysis
SCM	Yes	Moderate	Limited	Low
AHP	Limited	Low	Low	Low
ECF	Yes	Moderate	Moderate	Low to moderate
2–4 (24) Model	Limited	High	Low	Low
AcciMap	Yes	High	High	Low to moderate
SEM	Limited	Moderate	High	Low
ACT	Limited	Moderate	Low	Low
HFACS	Yes	High	Moderate	Moderate
CCA	Yes	Moderate	Moderate	Moderate
MORT	Yes	High	High	Moderate
STAMP	Yes	High	Very high	Moderate
Feyer and Williamson	Yes	High	Moderate to high	Low

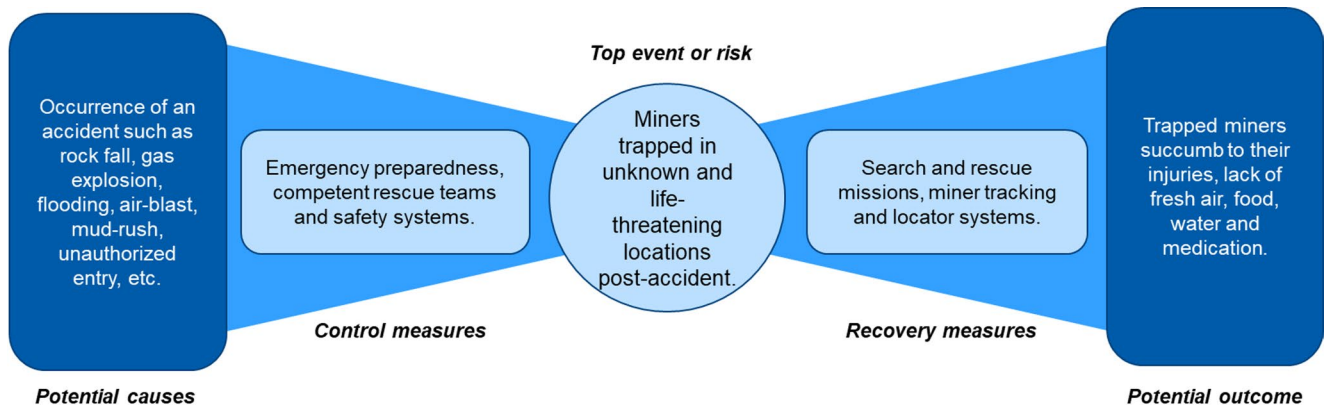


Fig. 3 Bowtie risk assessment for trapped miner accidents and fatalities

According to Alharbi et al. (2021), mortality rates from accidents can be reduced by improving the response time to trauma events. The response time is sensitive and has been enhanced by using faster modes of transport such as helicopters which has been beneficial for severely injured patients (Andruszkow et al. 2016).

A study by Wei et al. (2017) developed a model to estimate the possible number of people trapped in a collapsed building. This model is based on factors such as population density in the building, occupancy rates at the time of the earthquake (higher at night), the extent of damage, integrity of building, and the seismic intensity. Another study by Reinoso et al. (2018) assesses the expected loss of lives due to structural damage or collapse of buildings after earthquakes. These studies highlight the importance of the time-to-rescue period after an accident until medical care has been rendered. As a result, survival probability models have been developed to statistically estimate the survivability of patients. The commonly used models include the Life Table Estimator, the Kaplan-Meier Estimator and the Nelson-Aalen Estimator (Wiegrebe et al. 2024; Bewick et al. 2004; Bayraktar et al. 2023; Janurová and Briš 2014; Hu and Huffer 2020; Colosimo et al. 2002). These models can help understand, predict and analyze how long trapped miners can survive post-incident and identify factors that can affect their survival chances. They have also been used to estimate variables such as the time to failure for machines (Papathanasiou et al. 2023). These models represent the probability of survival beyond time t . Therefore, these models can be adapted for mine emergencies where miners are trapped underground.

Equation 1 is a non-parametric method used to determine the proportion of survivors at a specific point in time in comparison to the initial cohort of trapped miners. This is applicable to scenarios where the survival probability [$S(t)$] beyond a certain time (t) is binary and the available data is limited. This estimates the true survival function with no censoring of the dataset.

$$S(t) = \frac{\text{Number of survivors at time } t}{\text{Total Equation Number of trapped people}} \quad (1)$$

Equation 1 can then be rewritten in Eq. 2:

$$S(t) = \frac{n_{survivors}(t)}{n_{total}} = \frac{n_{survivors}(t)}{n_{survivors} + n_{fatalities}} \quad (2)$$

The survival probability at time t can be calculated using Eq. 3 (Wiegrebe et al. 2024; In and Lee 2018):

$$S(t) = 1 - F(t) = P(T > t) \quad (3)$$

Where:

$P(T > t)$ = the probability that a random variable T is greater than t .

$F(t)$ = the probability of a fatality (a miner has already died or recovered deceased) by time t .

T = random variable for the time until an event where a trapped miner is either rescued or dies.

t = specific point in time after the occurrence of an accident.

The Life Table Estimator model (Eqs. 4–6) groups survival time into intervals and estimates survival probabilities. This model has been used for analysis of occupational accidents in mining (Bayraktar et al. 2023). This model starts by calculating the termination probability using Eq. 4.

$$q_i = \frac{d_i}{n_i - \frac{w_i}{2}} \quad (4)$$

Then, it calculates the survival probability given by Eq. 5:

$$p_i = 1 - q_i \tag{5}$$

The cumulative survival probability is then calculated using Eq. 6:

$$S(t) = \prod_{j=1}^i p_j \tag{6}$$

Where:

- d_i = number of fatalities in intervals i .
- n_i = number of persons at risk at beginning of interval i .
- w_i = number of persons withdrawn at interval i .

The Kaplan-Meier Estimator model (Eq. 7) is another non-parametric method used to estimate survival probability over time (Hu and Huffer 2020; Colosimo et al. 2002). This method allows for the censoring of data. It provides a clear picture of how survival probability changes as rescue time increases. In this study, when some miners were rescued but the final outcome of others is unknown.

$$S(t) = \prod_{t_i \leq t} \left(1 - \frac{d_i}{n_i}\right) \tag{7}$$

Where:

- d_i = number of fatalities at t_i .
- n_i = number of persons exposed to the risk before t .

The Nelson-Aalen Estimator model estimates the cumulative hazard function $H(t)$ (Eq. 8). This model is often used alongside the Kaplan-Meier and the survival function models to compute and compare survival probabilities (Hu and Huffer 2020; Colosimo et al. 2002). The Nelson-Aalen model can be used to predict the increasing probability of death for the trapped miners as time elapses. This is based on an increasing hazard exposure of the trapped miners underground.

$$H(t) = \sum_{t_i \leq t} \frac{d_i}{n_i} \tag{8}$$

The cumulative hazard can be used to express the probability of survival in Eq. 9.

$$S(t) = \exp(-H(t)) \tag{9}$$

Overall, the Kaplan-Meier method, also known as the product limit, has been used mostly as an analysis and estimator tool for the expected time duration before an event such as death occurs (Colosimo et al. 2002). The Kaplan-Meier and Nelson-Aalen models are the most directly applicable models for analyzing and estimating the survivability of trapped miners post-accident. The Life Table Estimator model is useful for large-scale studies where exact times may not be available. In this case, these models were considered to

estimate the time duration that trapped miners can survive underground without rescue. In a typical underground mine, the after effects of an accidents such as compromised ventilation, poor visibility, and dense smoke should also be considered. Specific to mining accidents, a formula (given by Eq. 10) was derived to estimate the survival chances after a fire accident (Kissell et al. 1993). The focus was on the critical factors that can impact the survival chances of miners in the event of a coal mine fire incident.

$$I = (T_1 + T_2) - (T_3 + T_4 + T_5) \tag{10}$$

Where:

I = survival index for a specified fire situation and a specified miner.

T_1 = time for a fire to grow in size to a toxic concentration of fumes in the ventilation.

T_2 = time for fumes from the fire to circulate in the ventilation to the point of escape from the contaminated airway.

T_3 = time for fire detection.

T_4 = time interval between fire detection and the beginning of worker withdrawal.

T_5 = time for a miner to travel from original location to a point of escape from the contaminated airway.

Aims and objectives

The aim of this study was to empirically investigate and analyze global incidents involving trapped miners and evaluate the survivability of the trapped miners in these incidents. By applying empirical data and survival analysis methods, the study seeks to quantify survival probabilities, identify critical factors influencing outcomes, and highlight the importance of effective SAR operations in improving survival probabilities. Therefore, the objectives of the study were to:

- Demonstrate the severity and impact of the trapped miner incidents in underground mines.
- Compile and analyze the trapped miner incidents by commodity, mining method, initial event or cause, depth of entrapment and SAR durations.
- Estimate the survival probability of the trapped miners post-accident.

Methods

Trapped miner incidents data collection and quality of data

The trapped miner incidents data is not well defined nor readily available due to these incidents not being reported and recorded properly. Therefore, a critical part of this study was to gather and classifying data on these incidents to demonstrate their frequency and severity. The data was collected from 39 incidents involving trapped miners between 2006 and 2024. This included incidents from various mines in different countries around the world. The data was collected and consolidated from various sources including mining companies' reports and websites (specific mines that experienced the accidents), government agencies' reports and portals (official authority published reports), regulatory bodies, published journal papers, and online newspaper reports (Ngwenyama 2018). However, the newspapers reports are often not well researched and the information thereof can be inaccurate and inconsistent. To improve and ensure accuracy and quality of the data, multiple reports on the same incident were obtained to corroborate the reported information and ensure accuracy and consistencies. A study by Reinoso et al. (2018) also relied on data gathered from newspaper reports and literature to gather data on people trapped under rubble of collapsed buildings. However, there is still a marginal risk of error or inconsistencies with the data collected from the newspaper reports.

Data analysis and variables

The trapped miner incidents dataset was compiled following the layout structure used by Rom and Kelman (2020). In their study, the authors gathered and analyzed data about the entrapment of people resulting from 22 earthquakes between 1985 and 2015. The consolidated data of this study is classified and summarized in Table 13 in the Appendix. The dataset was also used to model several other scenarios in which miners can become trapped underground post-accident, as a function of the initial event. The trapped miner incidents dataset in this study was systematically classified and analyzed according to the following criteria:

- Commodity mined: To evaluate the likelihood of entrapments across different commodities and to assess which commodities are most associated with high-fatality rates.
- Mining method: To assess how the specific mining methods contribute to the risk of miner entrapment and evaluate which result in more severe consequences.

- Initial event or cause of the accident: To identify and analyze the primary incidents that led to the entrapments of miners as well as their frequency and impacts.
- Area of occurrence: To determine which sections of a mine are most likely to result in the entrapment of miners.
- Depth of entrapment: To assess if there is any correlation of the entrapments to the depth of the incident occurrence.

Figure 4 is a schematic description of the methodology that was followed for classifying and analyzing the data from the incidents. The following variables were defined for the analysis of the dataset:

n = number of incidents involving the entrapment of miners in underground mines.

N = number of trapped miners in these incidents.

t = time-to-rescue.

S = number of survivors.

$S(t)$ = the probability of survival beyond time t .

F = number of trapped miners who eventually died.

Survival probability Estimation

Many accident analysis studies focus on the causes and prevention of accidents and fatalities, as well as the safety systems and protocols to prevent or minimize the severity and frequency of accidents. Conversely, this study focusses specifically on systematically examining the factors that can affect or influence the survival chances of trapped miners underground post-accident. Therefore, the Kaplan-Meier Estimator, Nelson-Aalen Estimator, and the Life Table models were utilized to analyze global incidents data to statistically evaluate the post-accident survivability of trapped miners. These models were selected based on their applicability to analyze and model the time-to-event scenarios. In this study, this includes scenarios where the trapped miners were rescued or their survival status was unknown beyond a certain period. Specifically, the Kaplan-Meier Estimator model was used to estimate the survival probability of the trapped miners beyond a specific duration following an entrapment without assuming a specific statistical distribution based on the period of entrapment to an event, whether rescued, eventuating fatality or unknown outcome. The Nelson-Aalen Estimator model was used to estimate survival

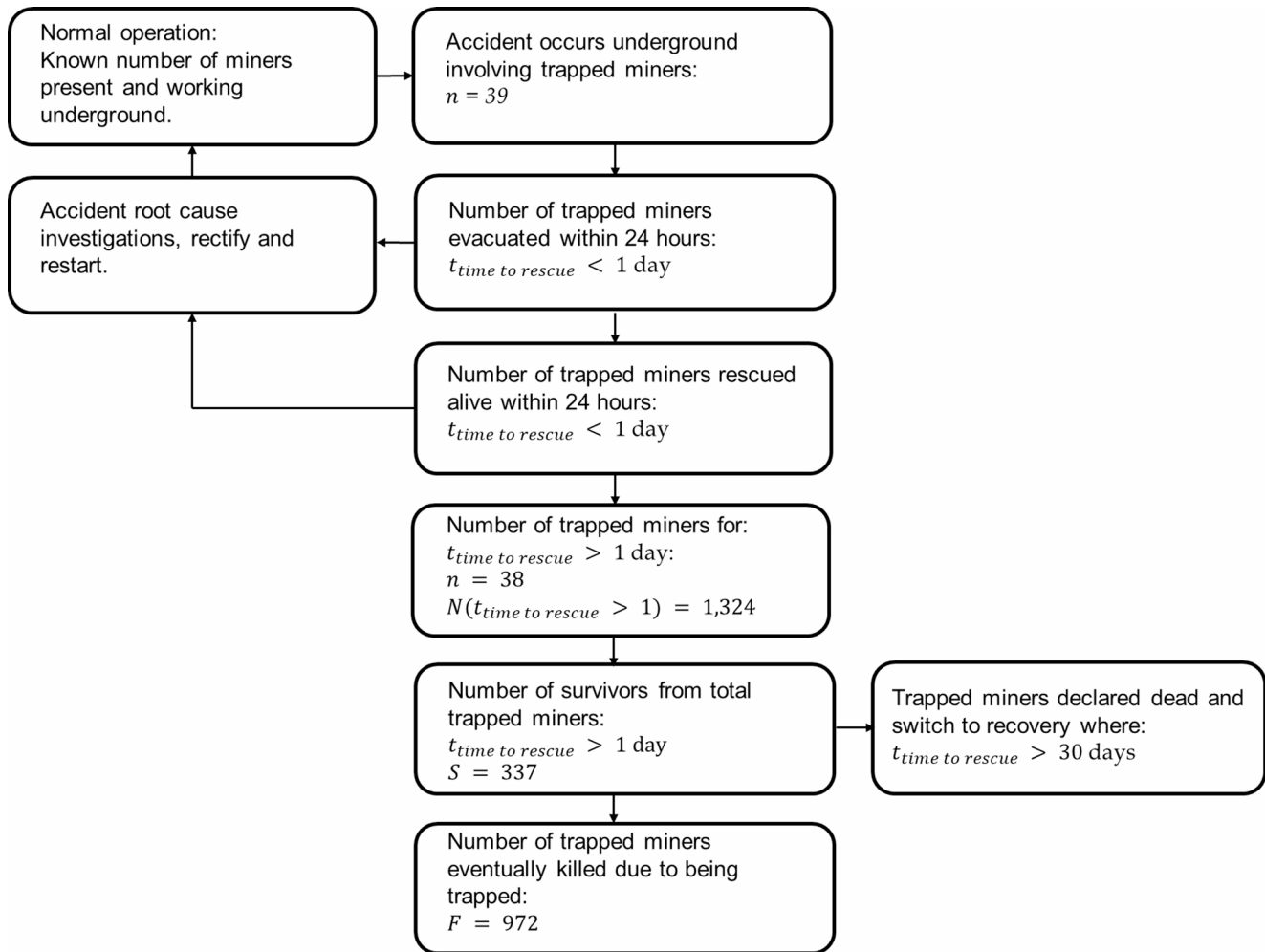


Fig. 4 Trapped miner incidents data collection and analysis methodology

probability based on the cumulative hazard to analyze the increasing risk during the entrapment period. The Life Table method was used to estimate the survival probabilities of the trapped miners over time intervals. Therefore, these methods were suitable for assessing the survival probabilities of the trapped miners over the entrapment or SAR duration. The MATLAB software was used to plot the models using the time-to-rescue based on the SAR duration data. These models utilized the SAR durations to model the survival probability of the trapped miners. This was used to compare rescue duration to the number of rescued miners to investigate if longer rescues correlate with survival rates.

Results

Trapped miner accidents

From the collected data, incidents involving trapped miners were identified ($n = 39$), with the number of trapped

miners ($N = 1,810$); in comparison to survivors ($S = 823$); and resulting fatalities ($F = 972$); were classified. Incidents in which the locations of trapped miners were known, and where they were rescued and evacuated alive immediately or within the same day ($t < 24 \text{ hours}$) were excluded from the data. This exclusion was based on the study’s focus on prolonged entrapment scenarios that necessitate SAR operations. These incidents involve greater risk to the trapped miners. By applying these criteria, only one incident was excluded from the data where 486 miners were trapped. In this incident, the locations of the trapped miners were known, there was constant communication between the miners and rescuers, and the miners were rescued and evacuated within 24 h. The remaining data set was $n = 38$. For incidents where the SAR operations lasted longer than 30 days or the trapped miners were never found, the SAR duration was capped at $t = 30 \text{ days}$. This is the duration in which the survival chances of the trapped miners are extremely low without any help or support from surface. In such incidents, the trapped miners were often presumed dead. The recovery

of bodies was not classified as a SAR operation after the 30-day period. As such, 14 of the accidents were capped at 30 days due to the SAR operations taking longer than 30 days. After applying the exclusion criteria, the total number of trapped miners obtained; $N = 1,324$ with survivors $S = 337$ (25.5%), and fatalities $F = 972$ (73.4%). Approximately 1.1% of the trapped miners were unaccounted-for after all SAR efforts. However, this could be due to the inconsistencies in the reported information regarding the total number of trapped miners. Figure 5 is a summary of the number of incidents per year, total number of trapped miners, survivors, the resulting fatalities.

The data was further classified by commodity mined, mining method, initial cause of accident and area of occurrence in the mine in Fig. 6. However, critical information such as the number of employees present at the time of the incident was not available for analysis. This can also be attributed to the lack of a uniform methodology or standardized reporting framework for the trapped miner incidents.

From Fig. 6, most of the trapped miner incidents occurred in the coal mines (56%), followed by the gold mines (28%), platinum group metals (PGMs) mines at 8%, then the nickel (3%), silver-lead-zinc (3%) mines, with the least incidents occurring in the copper-gold mines at 2%. The trapped miner incidents were positively linked between the commodity mined and the mining methods. For example, the longwall mining method, typically used in the coal mines,

recorded the highest portion of the trapped miner incidents (38%), followed by the conventional (breast and down-dip) mining methods used in the gold and PGMs mines (26%). Other mining methods such as cut-and-fill, drift, sub-level stope and hydro are commonly used in the commodities such as copper-gold, nickel and the silver-lead-zinc mines and were in the range 3–5%. Artisanal or illegal mining activities constituted 5% of these incidents while 13% of the mining methods were unclassified or unavailable from the reports.

Furthermore, the commodity and mining method were then linked to the initial event or the cause of the entrapments. A correlation was noted as a majority of the entrapments being caused by gas explosions. The gas explosions (36%) are common in coal mines which typically employ the longwall mining method. This was followed by rock fall (15%) incidents which are common in the conventional (breast or down dip) mining methods used in the narrow reef deep-level hard rock gold mines. However, some of the incidents such as water inundation, fires, mud-rush and shaft collapses; are possible in all commodities and the different mining methods.

The trapped miner incidents were further compared by area of occurrence in the mines, but these incidents can occur almost anywhere in the mine. However, certain sections of underground mines become too complex for SAR operations due to the labyrinthine layout of the mine,

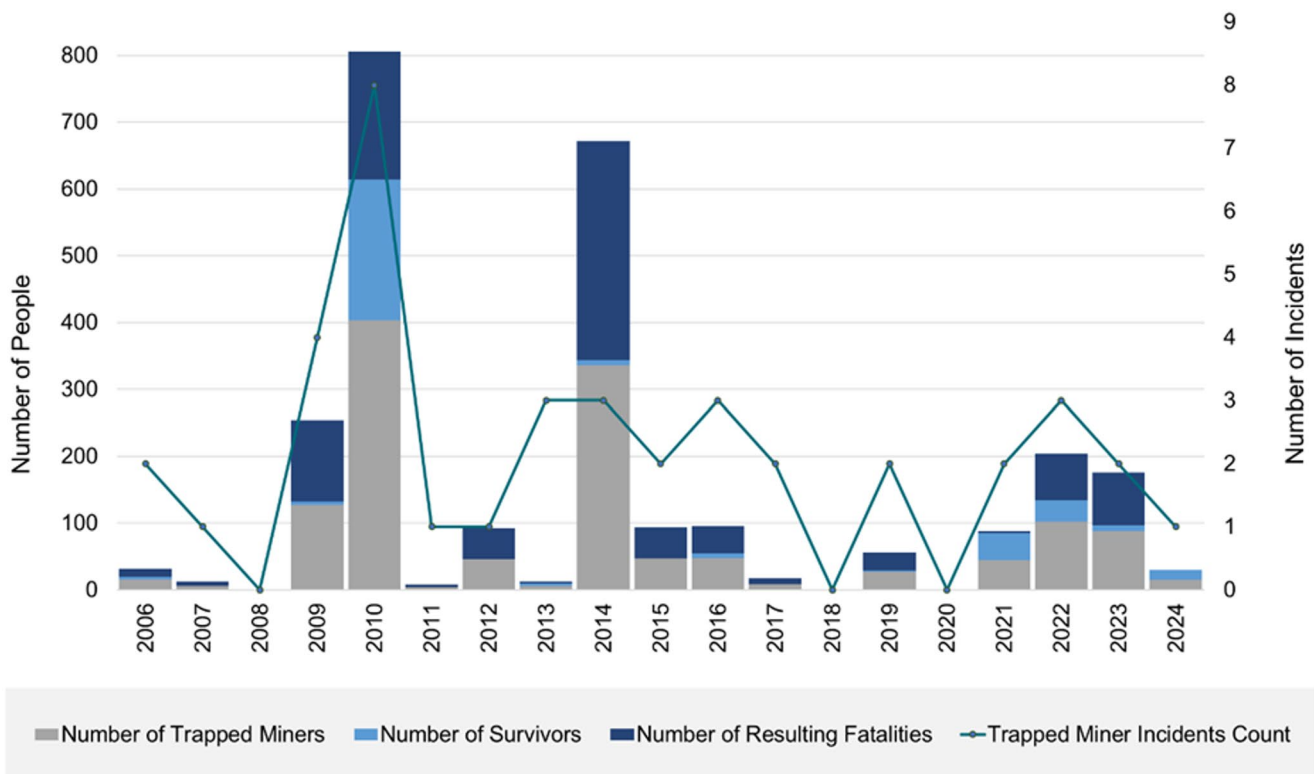


Fig. 5 Representation of trapped miners who are eventually fatally injured in comparison to survivors after SAR efforts

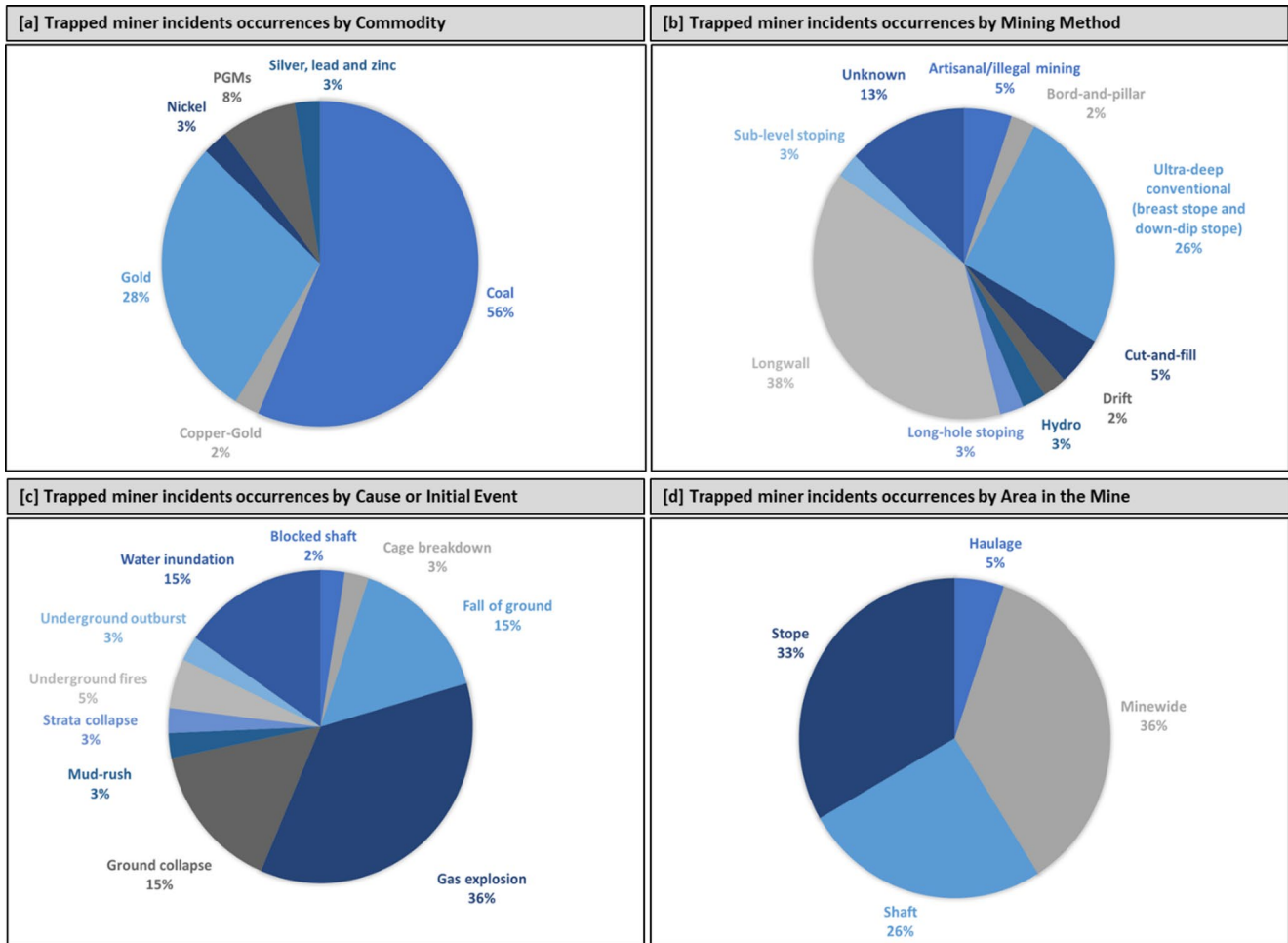


Fig. 6 Percentage distribution of trapped miner accidents by [a] Commodity mined, [b] Mining method, [c] Cause of accident and [d] Area of occurrence

ongoing developments and the continuous advancement of excavations. The majority of incidents were found to occur at active working faces such as stoping areas and development ends where mining activities are most concentrated. The stoping areas accounted for 33% of the incidents, with 26% occurring around the shaft area (including the lamp room incident at Lily mine) and 36% unidentified areas throughout the mine (mine-wide) including unknown areas and the least being 5% along haulages. The 2016 Lily Mine disaster is an example that miners can become trapped in unforeseen locations. This demonstrates the unpredictability and complexity of these incidents.

The unpredictability and complexity of these incidents necessitate the need to derive additional scenarios to better understand how miners can become trapped underground (Table 2). This was based on the historic data of the initial events. These scenarios were derived from the trapped miner incidents. It was noted that these scenarios can vary from one mine to another due to factors such as the magnitude of the accident, section in which the accident occurred,

and number of miners present in that section. In some cases, entrapments can occur due to health-related issues such as incapacitation or heat exhaustion. Each scenario presents unique challenges that can exceed the scope of standard emergency response. This necessitates the need for mine-specific rescue strategies.

Analysis of trapped miners and survivors

From the 38 accidents, the total number trapped miners ($N = 1,324$), the number of survivors ($S = 337$; 25.5%), and the number of fatalities ($F = 972$; 73.4%), as well as the average SAR durations in each classification were determined. Tables 3, 4, 5, 6 and 7 provide a comparison of the number of trapped miners, survivors and fatalities by commodity mined, mining method, area of occurrence, the initial event cause and the depth at which the incident occurred.

The highest number of trapped miners was recorded in the coal mines (82.8%; $N = 1,096$), followed by the gold mines (10.4%; $N = 138$), then in the nickel mines (2.9%;

Table 2 Possible trapped miner scenarios in underground mines

Initial event or cause	Subsequent trapped miner scenario
Fall of ground	<ul style="list-style-type: none"> • Person trapped behind a fall of ground (e.g. 2017 Tau Leko mine and 2016 Beaconsfield mine accidents) • Person buried in a fall of ground (e.g. 2016 Impala #20 shaft, 2007 Crandall Canyon mine and 2013 Bathopele shaft accidents)
Gas explosion	<ul style="list-style-type: none"> • Person lost due to being displaced by a gas explosion (e.g. 2006 Sago coal mine, 2010 Pike River mine, 2010 Wangjialing mine and 2015 Zasyadko mine accidents)
Underground fires	<ul style="list-style-type: none"> • Person lost or trapped in dense smoke • Person trapped due to fire (e.g. 2014 Doornkop mine accident)
Water inundation or intrush	<ul style="list-style-type: none"> • Person swept into an unknown location by an intrush (e.g. 2011 Gleison mine, 2014 Ermenek coal mine, 2010 Wangjialing coal mine and 2010 Luotuoshan coal mine accidents) • Person lost due to being submerged in a flood • Person trapped due to high levels of water
Air-blast	<ul style="list-style-type: none"> • Person displaced into unknown location with sustained injuries
Mud intrush	<ul style="list-style-type: none"> • Person swept away by an intrush of mud into an unknown location and submerged in mud
Poor visibility due to power outage or smoke ingress	<ul style="list-style-type: none"> • Person lost underground and unable to find escape route due to poor visibility as a result of power outage or smoke ingress into a working panel from burning conveyor belts
Machinery-to-person interaction	<ul style="list-style-type: none"> • Person struck by moving machinery unnoticed by colleagues and machine operator
Fell in cavities	<ul style="list-style-type: none"> • Person fell in a cavity such as an ore-pass without being noticed by colleagues
Novices or visitors	<ul style="list-style-type: none"> • Novices and visitors lost underground due to being separated from their host
Unauthorized entry into abandoned areas	<ul style="list-style-type: none"> • Person entering into an abandoned area without notifying the control room • Persons entering into abandoned areas for illegal activities that are not concerned with the mine
Illegal mining	<ul style="list-style-type: none"> • Illegal miners entering into abandoned mine or a mining area that has been sealed off (e.g. 2013 West Rand mine accident)

Table 3 Trapped miner accidents by commodity

Commodity	Number of trapped miners	% of trapped miners	Number of rescued miners (survivors)	% of rescued miners	Number of resulting fatalities	% of fatalities	Average of SAR duration (days)
	$N=1,324$		$S=337$		$F=972$		$t=14.9$
Coal	1096	82.8	193	57.3	888	91.4	19.6
Copper-Gold	33	2.5	33	9.8	0	0	17
Gold	138	10.4	61	18.1	77	7.9	9.6
Nickel	39	2.9	39	11.6	0	0	3
PGMs	16	1.2	9	2.7	7	0.7	7.3
Silver, lead and zinc	2	0.2	2	0.6	0	0	1

Table 4 Trapped miner accidents by mining method

Mining method	Number of trapped miners	% of trapped miners	Number of rescued miners (survivors)	% of rescued miners	Number of resulting fatalities	% of fatalities	Average of SAR duration (days)
	$N=1,324$		$S=337$		$F=972$		$t=14.9$
Artisanal/illegal mining	57	4.3	24	7.1	33	3.4	5
Bord-and-pillar	22	1.7	1	0.3	21	2.2	30
Conventional	54	4.1	22	6.5	32	3.3	7.4
Cut-and-fill	72	5.4	72	21.4	0	0	10
Drift	4	0.3	0	0	4	0.4	2
Hydro	31	2.3	2	0.6	29	3.0	30
Long-hole stoping	2	0.2	2	0.6	0	0	1
Longwall	959	72.4	187	55.5	757	77.9	16.9
Sub-level stoping	3	0.2	2	0.6	1	0.1	14
Unknown	120	9.1	25	7.4	95	9.8	29

Table 5 Trapped miner accidents by initial event or cause

Initial event of accident	Number of trapped miners	% of trapped miners	Number of rescued miners	% of rescued miners	Number of resulting fatalities	% of fatalities	Average of SAR duration (days)
	$N=1,324$		$S=337$		$F=972$		$t=14.9$
Blocked shaft	39	2.9	39	11.6	0	0	3
Cage breakdown	2	0.2	2	0.6	0	0	1
Fall of ground	28	2.1	10	3.0	18	1.9	10.4
Gas explosion	788	59.5	16	4.7	757	77.9	18.7
Ground collapse	137	10.3	83	24.6	54	5.6	15
Mud-rush	5	0.4	2	0.6	3	0.3	3
Strata collapse	6	0.5	0	0	6	0.6	30
Underground fires	17	1.3	8	2.4	9	0.9	2
Underground outburst	24	1.8	3	0.9	21	2.2	30
Water inundation	278	2.1	174	51.6	104	10.7	18.2

$N = 39$), the copper-gold mines (2.5%; $N = 33$), PGMs (1.2%; $N = 16$) and the least in the silver-lead-zinc mines (0.2%; $N = 2$). With regards to the rescued miners from the different commodities, 57.3% ($S = 193$) were in the coal mines, followed by gold (18.1%; $S = 61$), nickel (11.6%; $S = 39$), copper-gold (9.8%; $S = 33$), PGMs (2.7%; $S = 9$) and silver-lead-zinc (0.6%; $S = 2$). Additionally, when comparing the fatalities in the different commodities, the majority was in the coal mines which accounted for 91.4%

($F = 888$), with very few occurring in the other commodities such as 7.9% in the gold mines ($F = 77$) and 0.7% in the PGMs mines ($F = 7$) and 0% for copper-gold, nickel and silver-lead-zinc mines. The coal mines experienced the highest number of accidents and recorded the highest number of trapped miners and fatalities compared to the other commodities. The average SAR duration was also highest in the coal mines at 19.6 days, followed by the copper-gold mines (17 days), the gold mines (9.6 days), PGMs (7.3

Table 6 Trapped miner accidents by area of occurrence

Area of occurrence	Number of trapped miners	% of trapped miners	Number of rescued miners (survivors)	% of rescued miners	Number of resulting fatalities	% of fatalities	Average of SAR duration (days)
	$N=1,324$		$S=337$		$F=972$		$t=14.9$
Along haulages	43	3.2	33	9.8	10	1.0	23.5
Mine-wide	723	54.6	7	2.1	701	72.1	22.1
Shaft vicinity	233	17.6	105	31.2	128	13.2	11.3
Stope	325	24.5	192	57.0	133	13.7	8.5

Table 7 Trapped miner accidents by depth of entrapment

Depth of entrapment (m)	Number of Trapped Miners	Number of rescued miners	Number of resulting fatalities	Average of SAR duration (days)
20	15	15	0	4
60	10	0	10	30
80	3	0	3	30
85	13	1	12	2
113	153	115	38	8
127	22	1	21	30
150	73	11	62	18
200	4	0	4	2
265	5	2	3	3
300	145	12	133	16.8
350	2	0	2	5
390	77	56	21	14
400	461	13	448	18.2
457	6	0	6	30
500	40	22	18	30
540	30	0	30	30
600	24	0	24	30
700	79	33	46	10
780	36	0	36	30
900	2	2	0	1
925	3	2	1	14
1000	4	4	0	3
1200	39	39	0	3
1230	47	0	32	30
1300	9	1	8	4.5
1700	17	8	9	3
2300	0	0	0	1
3500	5	0	5	6

days), the nickel mines (3 days) and lastly the silver-lead-zinc mines (1 day).

When compared by mining method, the highest number of trapped miners was recorded in longwall mining (72.4%; $N = 959$) which is predominantly used in the coal mines. The number of trapped miners was fairly evenly distributed amongst the other mining methods with 72 in the cut-and-fill (5.4%), 57 in artisanal mining or illegal mining (4.3%), 54 in conventional mines (4.1%), 31 in hydro (2.3%), 22 in bord-and-pillar (1.7%), 4 in drift (0.3%), 3 in sub-level stoping (0.2%), 2 in long-hole stoping (0.2%), but 120 in

unclassified mines (9.1%). A similar trend was also noted for the survivors and fatalities where the average SAR duration was highest in the bord-and-pillar (30 days), hydro (30 days) and unclassified (29 days) mines but lowest in long-hole stoping (1 day), drift (2 days) and artisanal or illegal mining (5 days).

Again, the highest number of trapped miners occurred due to gas explosions (59.5%, $N = 788$) followed by water inundation (21%; $N = 278$) and ground collapse (10.3%; $N = 137$). This can be linked to the coal mines which are often highly susceptible to explosive gases. The longest SAR duration by initial event was due to outburst (30 days), strata collapse (30 days), water inundation (18.2 days) and gas explosions (18.7 days) with the lowest being cage breakdowns (1 day), underground fires (2 days), blocked shaft (3 days) and mud-rush (3 days). In terms of area of occurrence, the highest number of trapped miners occurred mine-wide (54.6%; $N = 723$), followed by stopes (24.5%; $N = 325$), shaft vicinity (17.6%; $N = 233$) and haulages (3.3%, $N = 43$). The survival chances surprisingly higher at the stopes (57%; $S = 192$), followed by shaft vicinity (31.2%; $S = 105$) with 9.8% ($S = 33$) and 2.1% ($S = 7$) in the haulages and mine-wide, respectively. However, the most fatalities occurred throughout the mine (72.1%; $F = 701$), followed by stoping areas (13.7%; $F = 133$), shaft vicinity (13.2%; $F = 128$) and lastly along haulages (1.0%; $F = 10$). The SAR duration was highest in along haulages (23.5 days) and mine-wide areas (22.1 days) in comparison to shaft vicinity (11.3 days) and stoping areas (8.5 days) on average. The SAR duration was expected to be higher at the stoping areas but this was not the case. There was no clear correlation for the depth of occurrence and the number of trapped miners, survivors and resulting fatalities. This shows that the number of trapped miners and fatalities depend on factors such as the magnitude of the accident and the number of miners present underground at the time of the event.

Survival and fatality rates analysis

The survival and fatality rates of the trapped miners were also evaluated by commodity mined, mining method, area of occurrence, the initial event as well as the depth of

Table 8 Survivability and fatality rates by commodity

Commodity	Number of trapped miners	Survivability rate (%)	Fatality rate (%)
Coal	1096	17.6	81.0
Copper-Gold	33	100.0	0.0
Gold	138	44.2	55.8
Nickel	39	100	0.0
PGMs	16	56.3	43.8
Silver, lead and zinc	2	100.0	0.0

Table 9 Survivability and fatality rates by mining method

Mining method	Number of trapped miners	Survivability rate (%)	Fatality rate (%)
Artisanal/illegal mining	57	42.1	57.9
Bord-and-pillar	22	4.5	95.5
Conventional	54	40.7	59.3
Cut-and-fill	72	100.0	0.0
Drift	4	0.0	100.0
Hydro	31	6.5	93.5
Long-hole stoping	2	100.0	0.0
Longwall	959	19.5	78.9
Sub-level stoping	3	66.7	33.3
Unknown	120	20.8	79.2

Table 10 Survivability and fatality rates by initial event of accident

Initial event of accident	Number of trapped miners	Survivability rate (%)	Fatality rate (%)
Blocked shaft	39	100.0	0.0
Cage breakdown	2	100.0	0.0
Fall of ground	28	35.7	64.3
Gas explosion	788	2.0	96.1
Ground collapse	137	60.6	39.4
Mud-rush	5	40.0	60.0
Strata collapse	6	0.0	100.0
Underground fires	17	47.1	52.9
Underground outburst	24	12.5	87.5
Water inundation	278	62.6	37.4

occurrence. Tables 8, 9, 10, 11 and 12 provide a representation of the survivors and fatalities from the initial cohort in the different categories. This provides an indication of the likelihood of miners surviving the conditions associated with the different commodities, mining methods, sections in the mine, the causes of the accidents as well as the depth of occurrence. These factors have an influence on the survivability of the trapped miners.

There was 100% survivability in the copper-gold mines ($N = 33$), nickel mines ($N = 39$), and silver-lead-zinc mines ($N = 2$) while coal was the lowest at 18% ($N = 1,096$), followed by gold at 44% ($N = 138$) and PGMs at

Table 11 Survivability and fatality rates by area of occurrence

Area of occurrence	Number of trapped miners	Survivability rate (%)	Fatality rate (%)
Along haulages	43	76.7	23.3
Mine-wide	723	1.0	97.0
Shaft vicinity	233	45.1	54.9
Stope or development end	325	59.1	40.9

Table 12 Survivability and fatality rates by depth of entrapment

Depth of entrapment (m)	Number of trapped miners	Survivability rate (%)	Fatality rate (%)
20	15	100.0	0.0
60	10	0.0	100.0
80	3	0.0	100.0
85	13	7.7	92.3
113	153	75.2	24.8
127	22	4.5	95.5
150	73	15.1	84.9
200	4	0.0	100.0
265	5	40.0	60.0
300	145	8.3	91.7
350	2	0.0	100.0
390	77	72.7	27.3
400	461	2.8	97.2
457	6	0.0	100.0
500	40	55.0	45.0
540	30	0.0	100.0
600	24	0.0	100.0
700	79	41.8	58.2
780	36	0.0	100.0
900	2	100.0	0.0
925	3	66.7	33.3
1000	4	100.0	0.0
1200	39	100.0	0.0
1230	47	0.0	68.1
1300	9	11.1	88.9
1700	17	47.1	52.9
3500	5	0.0	100.0

56% ($N = 16$). Clearly, the coal and gold mines are much riskier than the other commodities. There is higher fatality chance in the coal (82%) and gold (56%) mines. When compared by mining method, the fatality rates were highest in the drift (100%; $N = 4$), bord-and-pillar (95%; $N = 22$), hydro (94%; $N = 31$), longwall (79%; $N = 959$), unknown (79%; $N = 120$), conventional (59%; $N = 54$), artisanal or illegal mining (58%; $N = 57$) and sub-level stoping (33%; $N = 3$) mines. There were no fatalities recorded in the cut-and-fill and long-hole stoping methods. The workforce size was noted as a factor in the different mining methods. Mining methods with higher workforce size are more likely to report a greater number of trapped miners. Conventional

mining typically employs a larger number of personnel compared to mechanized methods.

The survivability and fatality rates were further assessed by the initial event or cause of accident. There was a 100% survivability rate for the blocked shaft ($N = 39$) and cage breakdown ($N = 2$) accidents but 0% for strata collapse. As expected, the survivability rate was as low as 2% for gas explosions. In accidents such as rock falls, mud-rush, fires, water inundation and outbursts, the survivability rate ranged between 10% and 70% depending on the magnitude of the accident. The survivability and fatality rates of the trapped miners were evaluated for the sections of the mine. The survival chances were found to be lowest for the mine-wide accidents at 1.0%. The mine-wide accidents include disastrous accidents such as explosions, hence these low survivability rates. The survival chances are highest when the accidents occur along haulages (77%; $N = 43$), followed stopes (59%; $N = 325$) and lastly the shaft area (45%; $N = 233$). Similarly, there was no correlation noted for the number of trapped miners and the depth of entrapment. The survival and fatality rates neither increased nor decreased with depth variation.

Survival probability estimation of the trapped miners

The Kaplan-Meier, Nelson-Aalen and Life Table models were used to estimate the likelihood of trapped miners surviving beyond a certain time following an accident. These models were used to plot and compare the survival probability [$S(t)$] of the trapped miners in relation to the SAR duration, t . Two binary conditions were defined:

- There were fatalities or no rescue [$fatality > 0$].
- The trapped miners were rescued or status is unknown [$censored = 0$].

The dataset uses the binary indicator to censor fatalities. The survival probability is plotted based on the occurrence of a fatality or rescue during the SAR operations. The SAR start time was defined as the time just after the occurrence of an accident. The end time was defined as the time at which SAR operation ended, whether rescue or fatality. The dataset was plotted based on the Kaplan-Meier Estimator (Fig. 7), the cumulative hazard (Fig. 8), the Nelson-Aalen Estimator (Fig. 9), as well as the Life Table (Fig. 10) models to compute the survival probabilities. An upper and lower confidence intervals (CI) of 95% were applied. All three estimator models were then compared in Fig. 11.

As expected, the survival probability of the trapped miners in all three models was seen to be decreasing with time. This is due to the compromised situation of the trapped

miner and exposure to secondary occurrences and hazards post-accident. At the start, where $t = 0$, the probability of survival is approximately 100% which decreases rapidly within the first 5 to 10 days. The most fatalities occur within the first 5–10 days of the entrapment. The probability of fatality accumulates faster during the early period of the entrapment. This shows the need for rapid deployment of efficient, effective, well-planned and adequately equipped SAR operations. Figure 7 shows the Kaplan-Meier survival curve with 95% confidence intervals. The curve illustrates a steep decline in survival probability during the first few days of entrapment. This demonstrates a critical importance of rapid and efficient SAR operations. The confidence intervals around the estimate provide an indication of uncertainty, especially in later time SAR intervals. Figure 8 is a representation of the Nelson-Aalen cumulative hazard estimate and its corresponding survival probability in Fig. 9. This demonstrates the increasing cumulative risk of fatality as time progresses and helps identify phases during which risk escalates exponentially. Figure 10 displays the Life Table estimate where SAR time intervals are grouped to compute the proportion of survivors. Lastly, the survival analysis estimate models are compared in Fig. 11. The Kaplan-Meier and Nelson-Aalen models show similar trends in early entrapment durations but begin to deviate in the latter part of the SAR duration. The Kaplan-Meier model provides precise event timing while the Nelson-Aalen model was useful for identifying cumulative hazard progression.

Discussion

Key learnings and observations from the trapped miner incidents show that the survivability of trapped miners underground post-accident depends on a number of factors. One of the ways to improve survival probability is the implementation of an efficient and effective SAR operation. Despite such necessity, it was observed that SAR operations can be significantly delayed by other factors and challenges such as the uncongenial post-accident conditions in the mine. Critically, SAR operations can also be significantly delayed by the lack of critical information such as the number of trapped miners and accurate locations of the trapped miners (as was seen in the Zasyadko, Shanxi, Yuangang and Luotuoshang mine accidents). In most of the mines, there was also no system in place to determine the locations and the exact number of the trapped miners. This forced rescuers to search in random areas or presumed locations. The SAR operations involve time-consuming activities such as drilling into presumed locations, using robotic vehicles, rescue dogs and flying drones (such as those used in the San Jose, Crandall Canyon, and Sago mine accidents).

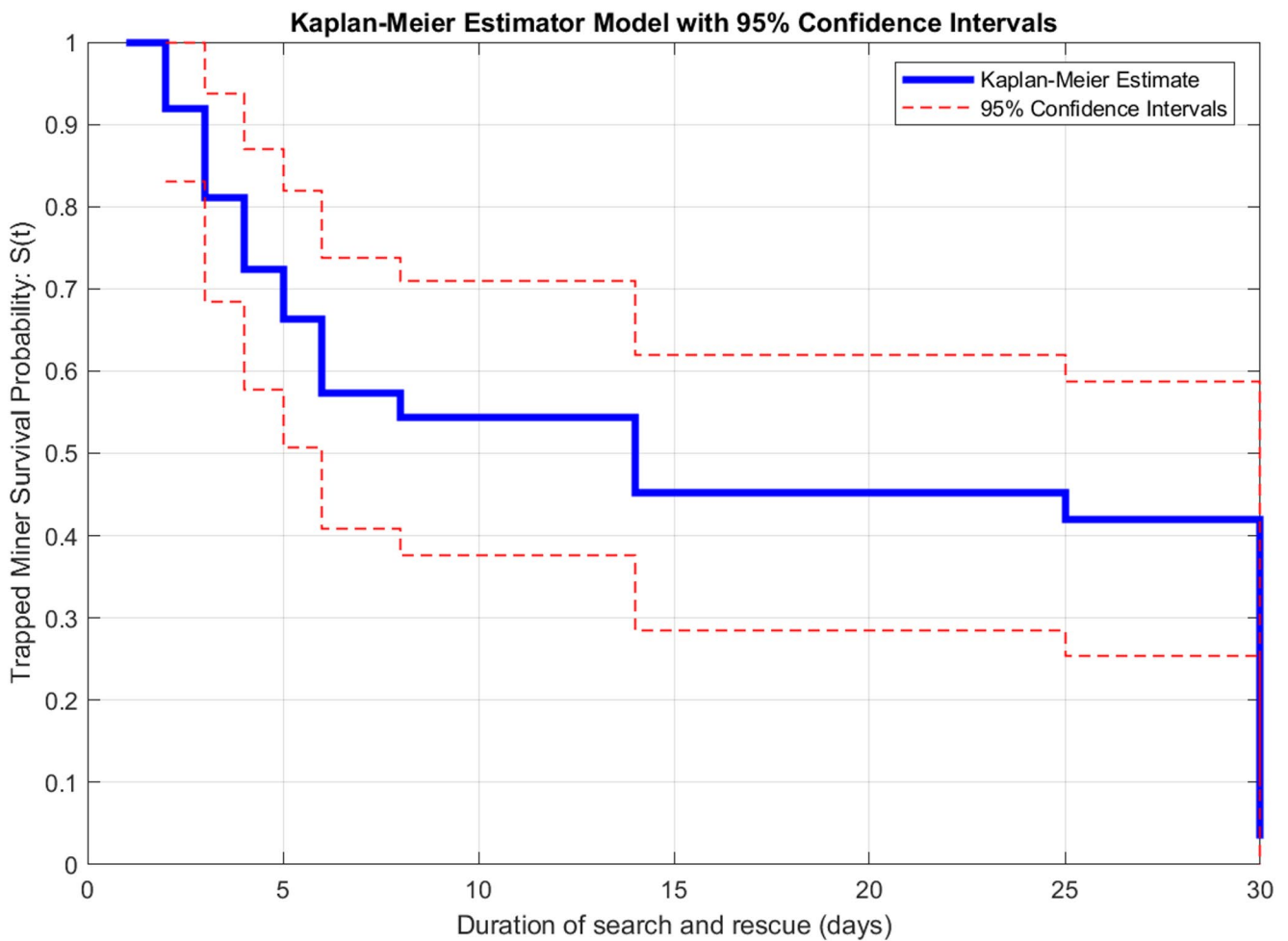


Fig. 7 Kaplan-meier estimator model

In some cases, the trapped miners include unregistered people such as illegal miners (as was seen in the Redwing and Yuanyang mine accidents). The largest number of trapped miners from a single incident was during shift change. In many cases, the physical health and mortality statuses of the trapped miners were unknown. Knowing their statuses can help rescuers prioritize rescue efforts to the trapped miners who may be still alive. Some SAR operations were suspended due to lengthy search. This led to the trapped miners being declared dead without evidence and with no further plans of retrieving bodies (e.g. Pike River and Henan mine accidents). Some of the SAR operations became too dangerous and risky for the rescuers. Some of the SAR operations were not well planned and prepared due to the lack of rescue funds and resources. This led to the halting of the SAR operations. Very few SAR operations were successfully executed, some were only successful by luck, and some failed completely. These incidents showed that trapped miners do their utmost best to stay alive and hope that help is underway (e.g. Beaconsfield and San Jose

mine accidents). Therefore, improving SAR response is critical for preventing fatalities related to the entrapment of miners.

The trapped miner incidents are unique and present new challenges each time they occur as a function of the initial event and the surrounding environment. This includes factors such as commodity mined, mining method, area of occurrence and number of miners present and working underground. Trapped miner accidents and fatalities are frequently reported and classified based on the initial event of an accident. However, miners may survive the initial event, but later succumb to secondary effects of being trapped. This suggests a need for a uniform and standardized reporting methodology and framework. This requires input parameters such as the initial event or cause of accident, the specific area within the mine where entrapment occurred, the size of the initial cohort, the number of trapped miners, number of survivors, SAR duration (from start time to the end), and the number of fatalities among the initial trapped miners cohort. In most of the incidents, there was no means

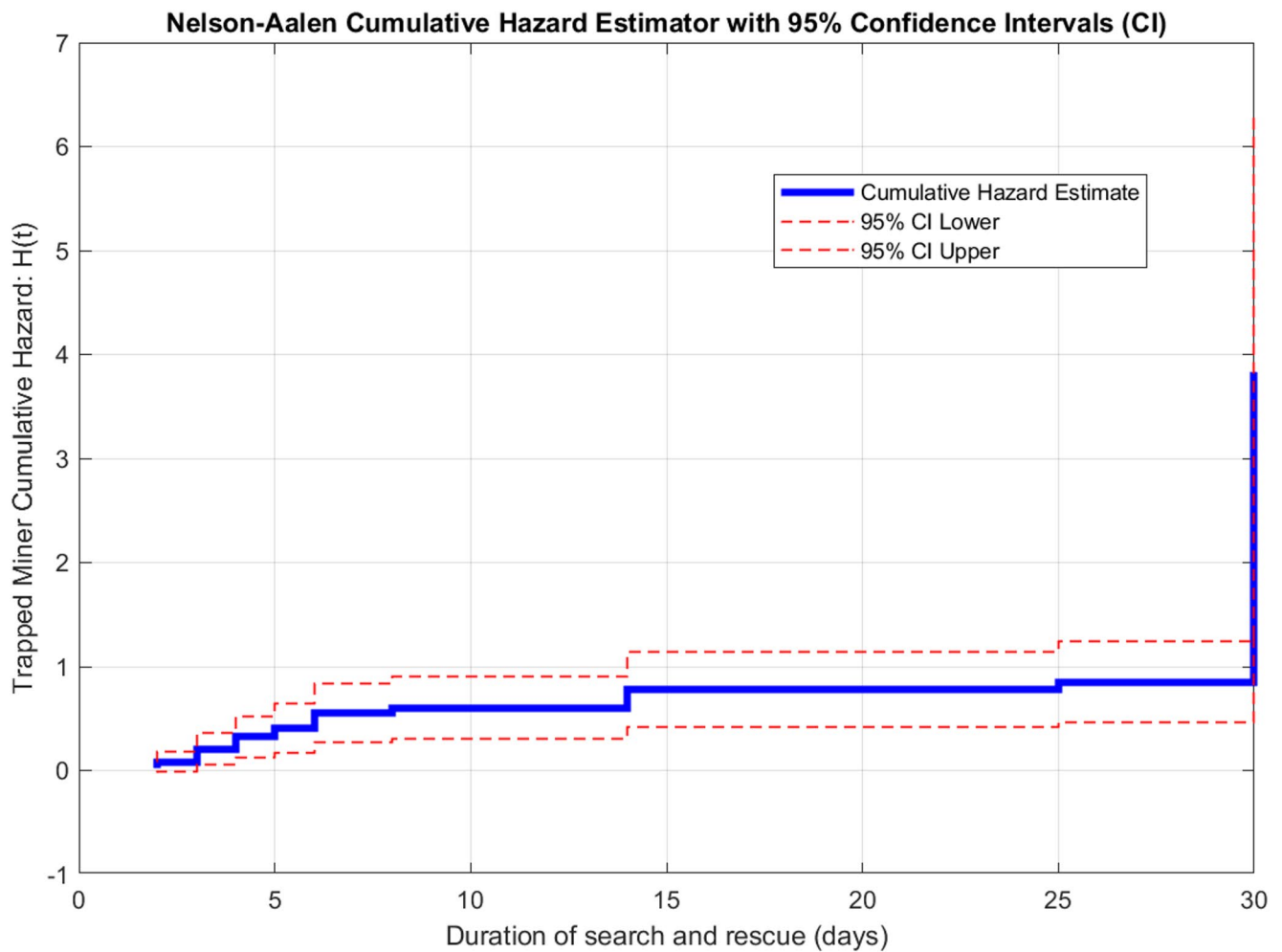


Fig. 8 Cumulative hazard on nelson-aalen estimator model

of helping rescuers prioritize rescue efforts between dead and alive trapped miners. This will require a system that can, not only track the locations of miners, but also monitor their vitals. This system can be used to locate trapped miners as quickly as possible in alignment with adequate emergency preparedness.

Additionally, an emergency preparedness framework is proposed to help with emergency preparedness where miners have become trapped underground (Fig. 12 in the Appendix). This starts with a mine-based risk assessment using the appropriate tools. Various trapped miner scenarios can be generated and simulated from the accidents data associated with the specific mine. This can then be used to develop an emergency rescue protocol and emergency rescue readiness plan based on the information gathered from the mine. The risk assessment and emergency rescue framework can be improved continuously with more data and further interventions. There is a critical need for a global standardized reporting framework for mine incidents involving trapped miners. This framework would ensure consistent data

on number of trapped miners, number of rescued miners, eventual fatalities, SAR duration. Another study is recommended to compare the survival probability of people in the mining industry to other high-risk industries. Investigate not only survival but also the long-term health, psychological, and occupational outcomes of rescued miners to understand the full impact of entrapment incidents. Future work could be focused on modelling decision-making processes during SAR operations. This can incorporate communication, coordination, and risk assessment by rescue teams to enhance the survivability of trapped miners.

Conclusion

This study shows that miners are not always killed during the initial event of an accident, but may survive and remain trapped or lost underground for an extended period. At this point, emergency SAR operations are required for improved survival chance of the trapped miners. The entrapment of

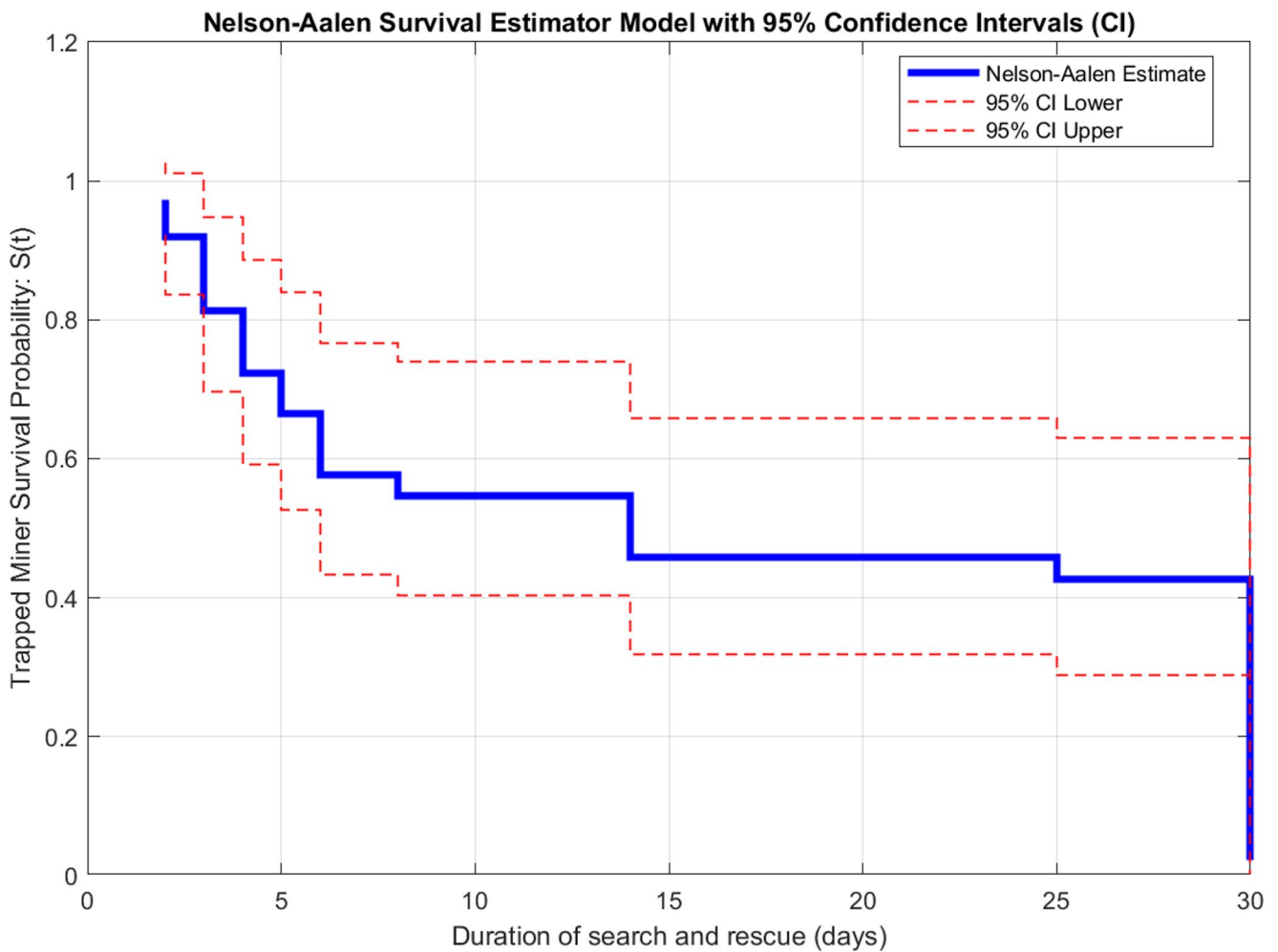


Fig. 9 Nelson-Aalen estimator model

miners in unknown locations increases SAR duration and the time-to-rescue and thus reduces the survivability probability. This study relied on publicly available reports and acknowledges the fact that many other relevant incidents may not have been covered in this study. This is because there are inconsistencies with reporting these incidents. This emphasizes the need for a standardized and detailed reporting framework to properly capture the data related to the trapped miner incidents. Although all the types of mines have the potential of trapping miners underground, the analyzed dataset showed that coal mines are the riskiest environment with the highest number of incidents and severity. This can be attributed to the gas explosion incidents which are highly destructive and have more chances of killing the trapped miners. The survivability and fatality rates of the trapped miners were found to be a function of the initial event of the accident. The Kaplan-Meier Estimator, Nelson-Aalen Estimator and the Life Table Estimator models showed the majority of fatalities occur within the first 5 to 10 days after an accident. This highlights a critical

interval during which timely rescue operations are most likely to save lives. The survival probability estimator models also provided an understanding and clearer depiction of how the survival probability decreases with time during entrapments. This was useful for visualizing the survival probability of trapped miners over the SAR period and how it decreases as the time-to-event increases. These findings emphasize the urgency of initiating SAR operations within the early phase of the entrapment. Any delays during SAR operations can significantly reduce the chance of survival. Being able to improve the survivability of trapped miners, the mining industry can benefit from: reduced the number of fatalities, reduced lost production time, avoid damage of the reputation of the industry, improved relationship with the state and regulators, trust from employees, and improved stakeholder confidence.

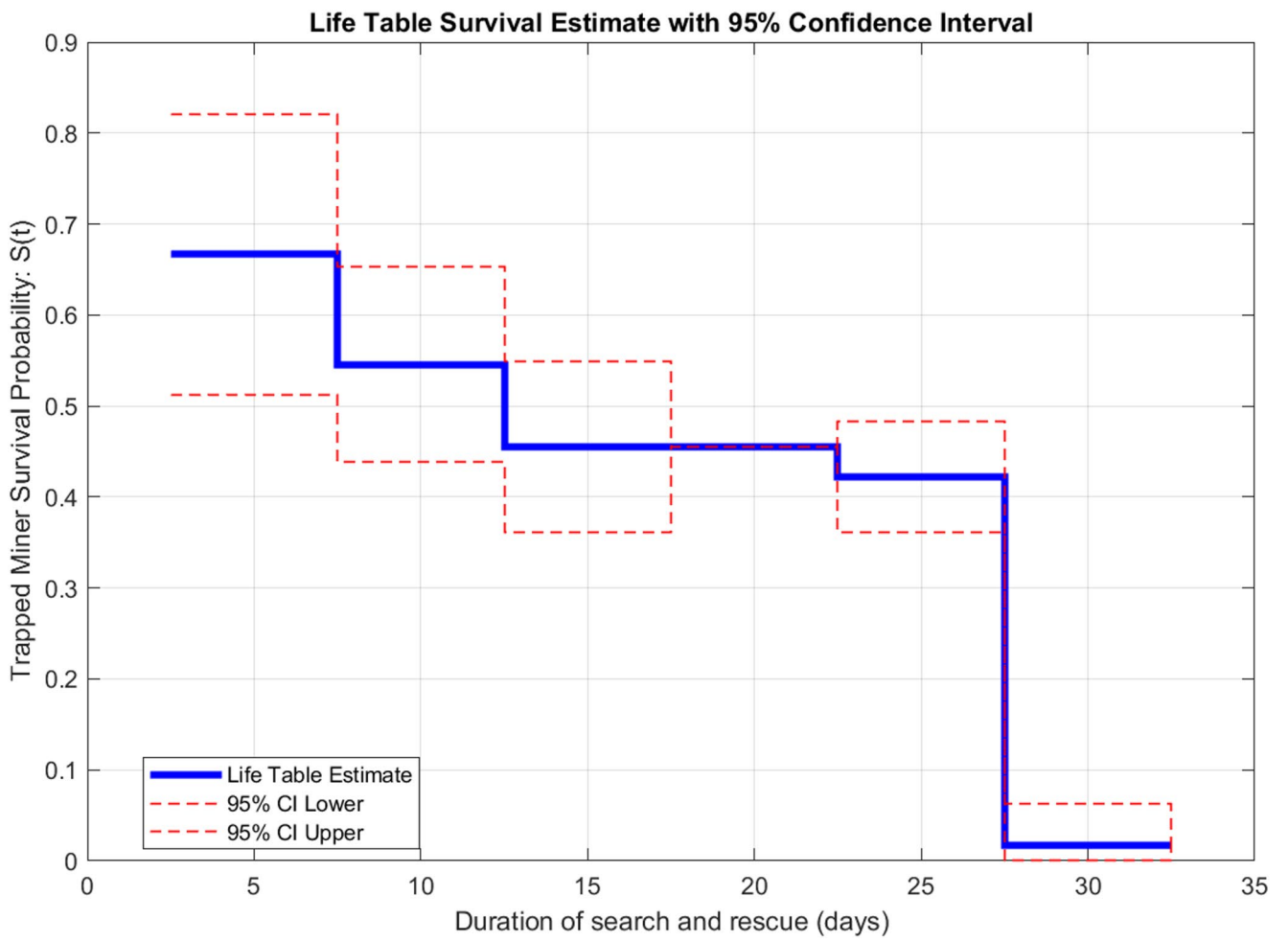


Fig. 10 Life table estimator model

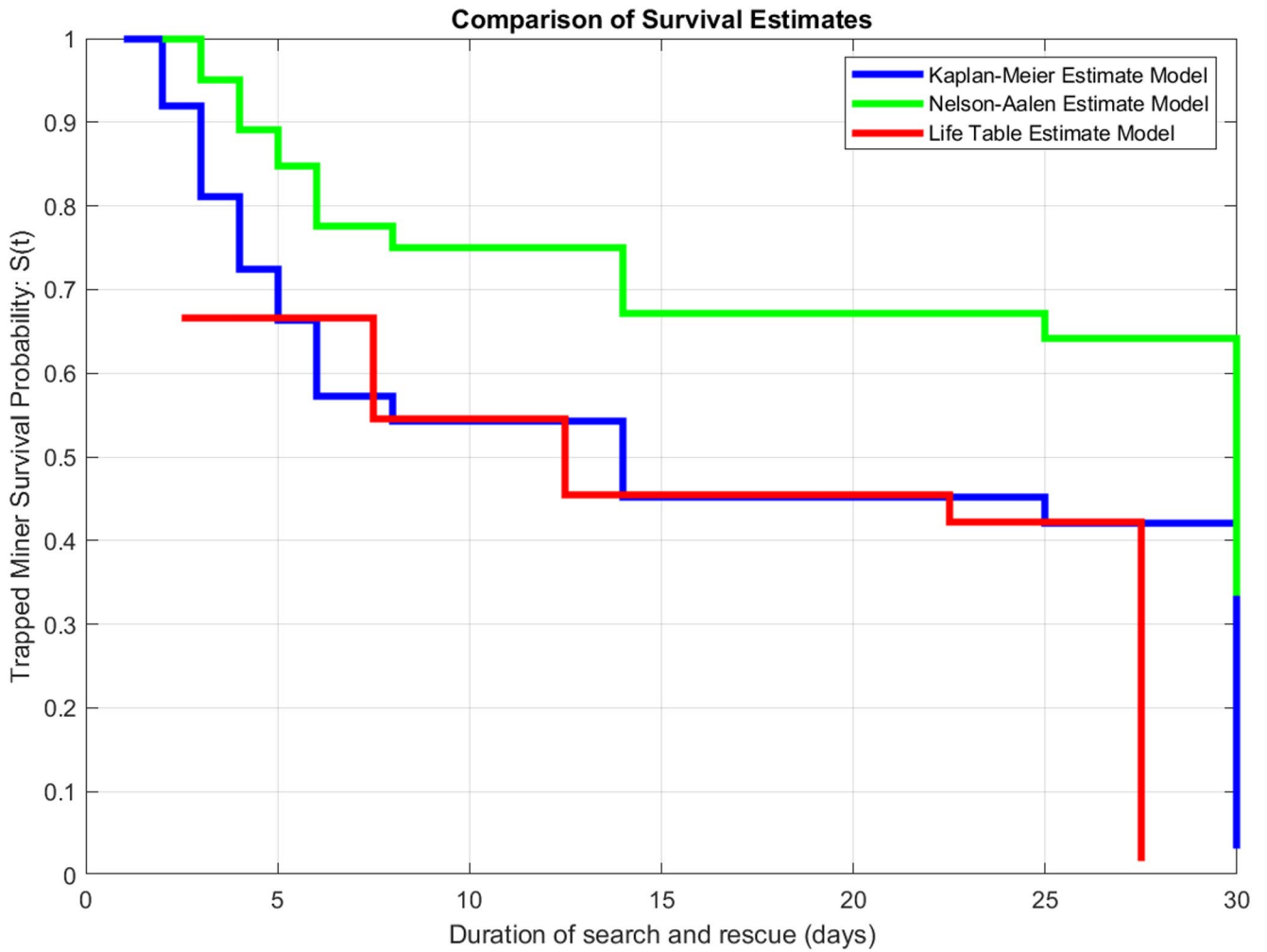


Fig. 11 Comparison of all estimator models

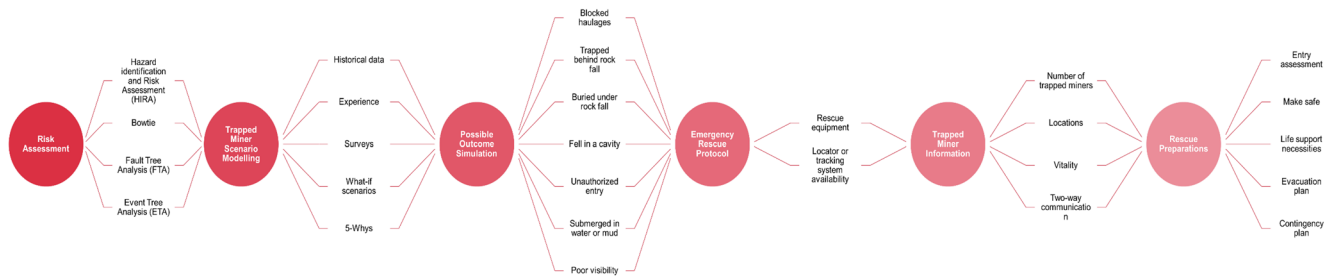


Fig. 12 Emergency rescue framework for trapped miners in underground mines

Appendix: incidents involving trapped miners in underground mines globally

Table 13 Trapped miner incidents in various countries around the world

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt and causes of failed and prolonged rescue attempt	Key observations and learnings
Redwing	Zimbabwe	04-Jan-24	Gold	20	Artisanal or illegal mining	Ground collapse	Shaft	15	15	0	4	A ground collapse accident occurred when 15 artisanal miners were working underground. SAR teams were deployed but were delayed by unstable ground conditions which made the operation challenging.	The exact number of miners trapped underground was unknown as they were not registered and recorded when entering underground. The artisanal miners used their experience to navigate inside the mine and able to survive for 4 days.
Kostenko	Kazakhstan	28-Oct-23	Coal	700	Longwall	Gas explosion	Mine wide	46	0	46	3	A gas explosion accident occurred when 252 miners were working underground. Of the 252 miners, 205 were evacuated immediately while 46 remained trapped underground and unaccounted for. A SAR operation was initiated to rescue the trapped miners with assistance from professional military rescue service.	The locations of the trapped miners were unknown and the rescuers had to search all over the mine, particularly in two parts of the mine 4000 m apart. The SAR operation was hampered by ensuing fires, rubble material and destroyed mining equipment. It could not be concluded that the trapped miners were killed instantly or from being trapped.
Bay Horse	Zimbabwe	29-Sep-23	Gold	150	Artisanal or illegal mining	Ground collapse	Shaft	34	9	21	6	A ground collapse accident resulted in the entrapment of 34 miners, 13 escaped, while 21 were trapped underground in the abandoned mine. There were 39 artisanal miners inside the tunnel when the accident occurred.	There were conflicting reports about the exact number of trapped miners. This is because there was no proper system followed in counting the artisanal miners entering the abandoned and disused mine.
Yining	China	24-Dec-22	Gold		Unknown	Ground collapse		40	22	18	Unknown	A ground collapse accident occurred when 40 miners were working in the mine resulting in 18 miners trapped underground while 22 were evacuated. More than 300 rescuers were deployed with more than 80 rescue vehicles, and 467 sets of emergency rescue equipment, and 6 drilling machines from local companies.	The 18 trapped miners were not found nor retrieved from underground after 14 days of rescue efforts. Experts suggested that the survival chances of the 18 trapped miners were very slim and are likely to be dead after 2 weeks of unsuccessful rescue operations.
Amasra	Turkey	14-Oct-22	Coal	300	Longwall	Gas explosion	Shaft	52	10	42	3	An explosion occurred when 110 people were working underground in which 58 escaped while 52 were trapped. A SAR operation was initiated to save trapped miners. The rescuers needed to contain the fire in order to locate the trapped miners.	The number of trapped miners was unclear. The fire after the explosion continued for a while and necessitated efforts to extinguish. The reporting did not provide a clear indication of the trapped miners against those who were killed instantly.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt and prolonged rescue attempt	Key observations and learnings
El Pinabete	Mexico	03-Aug-22	Coal	60	Unknown	Ground collapse and water inundation	Haulage	10	0	10	512	A collapse in the mine tunnel wall triggered water inundation into the mine and flooded throughout the mine, resulting in 10 miners trapped underground. A SAR operation was initiated to search for the trapped miners.	Significant water pumping was required from flooded shaft and was delaying SAR operation. It took 512 days to find the first two bodies after extracted 2.3 million cubic meters of rock and soil. Experts doubted the trapped miners were still alive.
Inpala Rustenburg No.6 shaft	South Africa	28-Nov-21	PGMs	265	Conventional	Mud-rush	Shaft	5	2	3	3	A mud-rush accident occurred at the shaft bottom vicinity of the mine resulting in 7 miners trapped underground. The miners were working at shaft bottom when the area became inundated as a result of a mud rush. SAR teams were deployed to search for the trapped miners. From the 7 trapped, 2 managed to escape the area with minor injuries while the other 5 remained unaccounted for.	The locations of the trapped miners were unknown and the rescue teams relied on presumed locations based on the area in which the miners were last seen by survivors and where they were expected to be working at the time of the accident. However, the incident occurred at the shaft bottom area and this made it difficult to presume the locations of the trapped miners. The trapped miners were almost presumed dead due to the nature of the incident as rescue efforts were hindered by accumulation of mud and blocking access.
Totten	Canada	26-Sep-21	Nickel	1 200	Cut-and-fill	Blocked shaft	Shaft	39	39	0	3	A scoop bucket being transported underground dislodged and blocked the shaft of the mine, a heavy scoop bucket crashed into the lift system and blocked the shaft. The trapped miners proceeded to refuge stations where they have had access to food and water.	The trapped miners managed to evacuate to the refuge bay and were provided with food and water. Trapped miners were in contact with people and rescuers on surface. This was a matter of getting them out rather than searching for them.
Tau Lekoa	South Africa	06-Dec-19	Gold	1 300	Conventional	Fall of ground	Stope	5	1	4	4	A seismic event measuring 0.8 on the Richter Scale caused a fall of ground accident that resulted in 5 miners trapped underground. SAR team were deployed to search for the trapped mine personnel.	Rescue teams searched for the trapped miners throughout the collapsed panel area. The rescued person had sustained serious injuries and could have been succumb if rescue was not rendered timeously. The trapped miners succumbed to the lack of oxygen and have eventually died before being rescued.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt and prolonged rescue attempt	Key observations and learnings
Gloria	South Africa	04-Feb-19	Coal	127	Bord and pillar	Gas explosion	Mine wide	22	1	21	Unknown	A gas explosion occurred in the abandoned mine trapping about 20 undocumented people who had accessed the mine illegally. SAR team were deployed to search for the illegal miners who were attempting to steal cables in a shut mine.	It was difficult to confirm the actual number of trapped persons as they were unregistered illegal miners. It was initially believed that it was 20 people trapped but later confirmed that it was 22.
Kusasalethu	South Africa	25-Aug-17	Gold	3500	Conventional	Fall of ground	Stope	5	0	5	6	A seismic event occurred due to a tremor of a magnitude of approximately 1.2 on the Richter scale which caused one of the underground stopes or panels to collapse, resulting in 5 miners trapped. The seismic event resulted in an approximately 10 m fall of ground in the one stope. There were approximately 3000 miners present underground and working in various sections of the mine during the accident. A SAR operation was initiated and focused at presumed locations. The only available information was the number of trapped persons and the panel in which they were believed to be working.	The trapped miners were assumed to be located in the collapsed panel where they were last seen working. This was confirmed by their colleagues who survived the accident. One of the survivors was quoted saying that he was fortunate to have survived the accident as he was fixing a water-supply pipe that feeds water to the collapsed panel. This person would have been assumed to be also trapped in that panel while he was outside the panel. The mine was fortunate that the trapped persons were actually trapped at their presumed locations. The mine was also fortunate that only one panel was affected and that this was during shift hours. The mine only relied on the clock in/clock out system that is currently used to track and identify the number of miners entering underground and those that were reported safe and returning from underground to determine the exact number of trapped miners.
Tau Lekoa	South Africa	22-Jul-17	Gold	1300	Conventional	Fall of ground	Stope	4	0	4	5	A seismic event occurred and resulted in four miners being trapped underground due to a fall of ground. The accident happened on a Saturday when the trapped miners were working overtime. A SAR operation was initiated in the proximity of the collapsed panel. Rescue teams were deployed to search for the trapped persons in the areas where they were last seen working.	The trapped persons succumbed to their injuries due to the long-lasting SAR operation. The rescue teams did not have accurate locations of the trapped persons which would have resulted in a quicker rescue operation.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt failed and prolonged rescue attempt	Key observations and learnings
Impala Rustenburg No.1 shaft	South Africa	17-May-16	PGMs	400	Conventional	Fall of ground	Slope	9	7	2	14	A fall of ground accident occurred covering a 30 m by 40 m mining area collapsed. When the accident occurred, nine miners were initially trapped underground. Seven of the nine miners were rescued immediately after the accident. These miners were rescued through normal emergency evacuation procedures by the rescue teams. A SAR operation was conducted close to the area that had collapsed. Rescue teams had to remove large rocks to try and locate the trapped workers based on the presumed locations in which they were believed to be located before the accident occurred.	The exact area in which the persons were trapped was presumed, but the exact locations of the trapped persons were unknown. The rescue teams searched in random areas within the collapsed area. This resulted in a prolonged search operation. Rescue teams worked day-and-night clearing a path to access the area where the miners were believed to be trapped. The rescue teams used a proximity detection system in an attempt to locate transponders placed inside the helmets of the mine workers. However, this approach did not succeed in locating the trapped miners.
Severnaya	Russia	25-Feb-16	Coal	780		Gas explosion	Mine wide	31	0	36	Never found nor recovered	There were 111 people working underground when the accident occurred in the mine followed by a series of further explosions occurred. Special robotic equipment, equipped with several video cameras, gas sensors and infrared sensing devices were deployed underground to survey the mine for damages and determine if it was safe for rescue teams to re-enter.	The SAR operations were declared dangerous and risky as it resulted in 5 rescue personnel killed while searching for the trapped miners. At least 500 people were called to the mine to assist with the rescue operation. At this time, it was believed that the trapped miners would not survive the explosions.
Lily	South Africa	05-Feb-16	Gold	80	Conventional	Ground collapse and sinkhole	Shaft	3	0	3	Never found nor recovered	A subsidence collapse accident occurred near the entrance of the mine after a crown pillar collapsed. The collapse caused a cave-in of an 80 m depth of rock material that trapped a container in which three mine workers were working. Various rescue attempts were tried with no success, even though the location of the trapped miners was known or predicted. Rescue attempts such as flying drones and drilling into presumed locations failed. The trapped person are trapped inside a container that they were worked in at the time.	A total of 76 underground miners were rescued after the accident and brought to surface safely. The rescued miners were retrieved through a ventilation shaft of the mine. However, the three surface workers disappeared into the sinkhole during the collapse with the lamp room container. Unstable ground conditions caused delays during the SAR operation. The workers were trapped in a ground collapse due to a partially mined crown pillar. The exact location of the container was known but kept shifting with the continuous collapse of ground.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt and prolonged rescue attempt	Key observations and learnings
Zasyadko	Ukraine	04-Mar-15	Coal	1200	Longwall	Gas explosion	Mine wide	32	Unclear	32	Unknown	The accident was caused by a gas explosion when 230 people were working underground. A SAR operation was initiated, and the bodies of the trapped persons were slowly recovered in the process. SAR operations recovered over 200 bodies. It was believed that there were still 32 miners trapped underground.	Various reports gave different figures regarding the exact number of trapped persons. It was unclear as to how many people were trapped underground. There were conflicting reports over the actual number of miners fatally injured and those trapped. The first report indicated that 23 people died instantly while other sources reported that about 50 miners were still trapped underground.
Kussalethu	South Africa	22-Feb-15	Gold	2300	Conventional	Underground fires	Stope	486	486	0	1	A fire broke out during maintenance work on one of the bulk air-cooler on level 75 in the mine. At the time of the accident, all miners were notified and advised to follow normal emergency escape procedures and to withdraw to the nearest refuge bays. Rescue teams were deployed to contain the fire.	The locations of the trapped miners were unknown. The trapped persons could not be detected easily due to smoke from the fire. A total of 486 mineworkers were trapped by the fire and this required adequate sizing of rescue efforts. All employees were safely rescued and brought to surface without injuries.
Ermenek	Turkey	28-Oct-14	Coal	300		Water inundation	Mine wide	18	0	18	6 months	The accident was caused by a broken water pipe that flooded the mine resulting in 18 miners trapped while another 20 miners escaped from the accident. Rescue teams were called to rescue the trapped miners. A SAR operation was initiated as the locations of the trapped miners were unknown.	The chances of survival of the trapped persons were declared slim due to the magnitude of the accident. Only two bodies out of the 18 trapped miners were located and retrieved from underground. Further 10 bodies were retrieved a month later. The last bodies were recovered nearly six months after the mine was flooded.
Soma/Eynez	Turkey	13-May-14	Coal		Longwall	Gas explosion	Mine wide	787	486	301	4	An explosion occurred during shift change while there were 787 people present underground at the time. A SAR operation was affected by smoke which caused poor visibility. The bodies of the miners were retrieved four days after the accident. The fires continued to burn for 3 more days and made it difficult for the rescue teams to locate the trapped miners. It was believed that a majority of the miners were killed instantly but some may have survived for a few days.	Most of the miners were killed from carbon monoxide poisoning. The number of people underground at the time of the explosion was uncertain. This is due to the large number of people present underground during shift change, some having exited while others still entering the shaft. Following the accident, rescue teams were deployed to the mine. The miners were believed to be trapped approximately 4000 m from the mine entrance.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt failed and prolonged rescue attempt	Key observations and learnings
Doornkop	South Africa	04-Feb-14	Gold	1700	Conventional	Underground fires	Stope	17	8	9	3	A shaft fire accident caused by a fire break-out occurred in the mine and was followed by a fall of ground accident resulting in trapped 17 miners. A SAR operation was initiated to search for the trapped miners. Rescue teams searched for the trapped workers in various workplaces due to not knowing the exact locations of the trapped miners.	Search progress was hampered by smoke and subsequent rock falls, and this made it difficult to locate the trapped persons. The rescue teams struggled to see through the smoky areas. The fire occurred at a stope (working face) on level 192 that intersected a main intake haulage.
West Rand	South Africa	25-Nov-13	Gold		Conventional	Ground collapse	Shaft	4	4	0	3	The accident occurred at an old, unused shaft. The trapped persons had entered the mine illegally. Rescue teams were deployed to SAR illegal miners. The rescue teams had to search for an unknown number of trapped persons and in random areas.	The trapped persons were illegal miners who entered an old shaft illegally. The number of trapped persons could not be determined.
Bathopele	South Africa	20-Jul-13	PGMs	350	Breast and Bord and pillar	Fall of ground	Stope	2	0	2	5	A fall of ground accident resulted in two miners being trapped underground. Rescue teams were deployed to locate and rescue the trapped miners. The rescue teams searched at the proximity in which the fall of ground occurred as a starting point to locate the trapped workers.	The mine personnel were trapped and killed while working at the face. The information used to locate the trapped workers was presumed and could not guarantee success in locating and rescuing them in time.
Xiaojiaowan	China	29-Aug-12	Coal	400	Longwall	Gas explosion	Mine wide	46	Unclear	Unclear	Unknown	At the moment of explosion there were 154 miners working at the mine. The launched SAR operations were severely delayed by the blockage of underground access. More than 300 rescuers have taken part in the rescue operation.	Rescue teams were required to wear gas masks because the area was smoky, and this affected visibility to locate trapped persons. Rescue operations are complicated due to high temperatures.
Gleision	Wales	15-Sep-11	Coal	200	Drift	Water inundation	Mine wide	4	0	4	2	The accident occurred while seven miners were working. The volume and speed of the water inrush trapped four of the six miners while the other two managed to escape to surface. A SAR operation consisted of rescuers from neighbouring mines and equipment suppliers.	The trapped miners were slightly submerged in silt and could not be easily seen. The mine did not have all the necessary resources to conduct the SAR operation and relied on external help. The mine plans appeared to be inaccurate when it was used to search of the trapped mine workers. The miner who escaped travelled a long distance to reach the surface.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt failed and prolonged	Key observations and learnings
Pike River	New Zealand	19-Nov-10	Coal	150	Hydro	Gas explosion	Shaft	31	2	29	Never found nor recovered	A series of gas explosions trapped 31 miners. A SAR operation was initiated, but it was delayed as rescue teams were attempting to enter the mine. The rescue operation was stopped as it was declared impractical and very unsafe for the rescue teams. Rescue attempts launched included drilling into presumed locations, robotic scouting and SAR operations. Four robotic vehicles were hindered by water accumulations and cave-ins.	There was no means of detecting whether the trapped miners were still alive or dead before the search operation was suspended. During the series of these explosions, the exact number of people remaining underground was unknown. Different sources reported various figures which were incorrect ranging between 25 and 33, but it was eventually confirmed that there were 31 miners. A borehole was drilled to an area in which the miners were believed to be located.
San Jose	Chile	05-Aug-10	Copper-Gold	700	Cut and fill	Ground collapse	Haulage	33	33	0	69	A ground collapse resulted in 33 miners (now known as "The 33") trapped underground. The trapped miners attempted to escape through a ventilation shaft system but failed due to the shaft experiencing ground movements. SAR operations were initiated to save the trapped miners who were believed to be still alive. Various rescue attempts were initiated including drilling several boreholes in different depths, positions and directions from surface.	A second collapsed delayed rescue and forced the rescue team to try an access the mine via a ventilation shaft. Drill rigs were taken to drill boreholes to locate and rescue the trapped miners. The 33 trapped miners managed to escape the accident and moved into a refuge chamber. The refuge bay was resourced with survival items such as canned foods and water, and this played a critical role in keeping the trapped miners alive.
Karadon	Turkey	17-May-10	Coal	540	Longwall	Gas explosion	Mine wide	30	0	30	8 months	A gas explosion resulted in 30 trapped miners who were working underground at the time of the accident. An initial SAR operation recovered 28 bodies after 4 days while others remained in unknown locations.	The duration of retrieving the remaining two bodies lasted for up to eight months. Even though it is likely that the miners were killed instantly by the explosion, there was still a need to retrieve their bodies.
Yuanyang	China	13-May-10	Coal	400	Longwall	Underground outburst	Mine wide	24	Unlear	21	Unknown	An underground outburst occurred when 31 miners were working underground resulting in 24 miners trapped underground while 7 of them escaped. Rescue teams conducted SAR operations throughout the mine, at random areas.	It was difficult to determine the exact number of trapped miners and their identities. The rescue teams searched for the trapped miners in random areas throughout the mine. An unknown number of illegal miners was also underground at the time of the accident.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt and causes of failed and prolonged rescue attempt	Key observations and learnings
Raspadskaya	Russia	08-May-10	Coal	600	Longwall	Gas explosion	Mine wide	24	0	24	Unknown	There were 359 people working when a gas explosion occurred. A SAR operation was launched. A secondary explosion occurred resulting in 20 rescue workers also being trapped underground. Rescue efforts were suspended after the second explosion.	Rescue teams searched for the trapped persons in locations where they were last seen. There were up to 560 rescuers involved. The rescue teams searched in random areas due to not knowing the locations of the trapped miners.
Upper Big Branch	United States	05-Apr-10	Coal	300	Longwall	Gas explosion	Stope	31	2	29	4	A coal dust explosion occurred resulting in 29 out of 31 miners killed. A SAR operation was initiated to locate and rescue the trapped miners. Boreholes were drilled in the process.	Rescue teams drilled boreholes to the affected areas in which the trapped miners were presumed to be located. The remaining four trapped workers were found after four days.
Wangjiating	China	28-Mar-10	Coal	113	Longwall	Water inundation	Stope	153	115	38	8	A water inrush accident occurred when 261 miners were working underground resulting in 153 miners trapped while 108 miners managed to escape shortly after the accident. A SAR operation was initiated, and it consisted of over 3 000 rescuers. The rescue teams managed to save 115 miners while 38 of them could not be saved and remained trapped.	Rescue operations were delayed by poor visibility, mud, turbulent water and low oxygen. After a week of being trapped, 9 workers were rescued alive and relied on eating coal to survive. Some of the trapped miners had been located, but there were difficulties in approaching them. The accident resulted in 38 deaths and 115 survivors rescued after being trapped underground and surviving for 8 days.
Luotuoshan	China	01-Mar-10	Coal	390	Longwall	Water inundation	Stope	77	56	31	14	The mine was flooded when 77 miners were working underground after they holed into a large pool of water contained within the rock. A SAR operation lasted for two weeks without locating the trapped miners. Rescue teams of 20 384 were busy pumping water out of the mine and attempting to stop the flooding after the rescue efforts were called off. Infrared surveillance cameras and echo megaphones were used to try to detect the trapped miners.	Up to 3 850 cubic meters of water were being pumped out every hour since the rescue efforts began, with around 100 000 cubic meters of water remaining in the mine. A continued inflow of water affected the rescue operation. Rescue efforts were stopped after 14 days as the medical teams believed that the 31 trapped miners had no chance of survival. There were still no signs of life after the two-week long rescue operation. The rescue operation was declared a failure and the trapped miners could not be located.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt and causes of failed and prolonged rescue attempt	Key observations and learnings
Perilya	Australia	22-Sep-09	Silver, lead and zinc	900	Long hole stoping	Cage breakdown	Shaft	2	2	0	1	A cage breakdown accident resulted in 2 miners trapped when the mine experienced power outage. The miners were rescued on the same day.	The locations of the trapped miners were known very well. This was a matter of rescuing the trapped miners.
Henan	China	08-Sep-09	Coal	300	Longwall	Gas explosion	Mine wide	44	298	Unclear	Unclear	A gas explosion occurred, killing 44 while 35 were trapped underground. A SAR operation was launched to locate an unknown number of workers. Later reports indicated the total death toll was confirmed to be 67 and 9 miners were still trapped. It is still unknown whether these miners were ever found, and their bodies retrieved from underground.	There were inconsistencies regarding the number of trapped persons and those who had died after the explosion. During the time of the explosion, there were 446 people working in the mine. A total number of 298 miners managed to escape. After the explosion, 56 miners were reported dead while another 92 were trapped underground.
Xinqiao	China	17-Jun-09	Coal			Water inundation		16	3	25		The mine became flooded when 16 miners were working underground. Rescue workers cracked open a collapsed tunnel at the mine. Rescuers recovered one body a week later and are still searching for the 12 other men.	From the 16 trapped miners, 3 were found alive after 25 days of being trapped in the flooded mine while 1 body was recovered. The miners were trapped for 604 h and this was declared as a miraculous survival.
Tunlan	China	21-Feb-09	Coal	400	Longwall	Gas explosion	Mine wide	436	362	77	6	A gas explosion occurred when 436 miners were working underground requiring 100 rescuers were deployed due to the large number of miners trapped and trapped underground. The progress of the rescue operation was being blocked and delayed by a fire in the shaft where the rescue teams were supposed to enter.	The rescue teams included a team of divers that continued the search for the trapped miners. There was an unclear indication of the total number of trapped persons. The unclear number of trapped persons could have affected the sizing of the required rescue efforts.
Crandall Canyon	United States	06-Aug-07	Coal	457	Longwall	Ground collapse	Stope	6	0	6	Never found nor recovered	A ground collapse accident left 6 miners trapped underground at a depth of 457 m and approximately 5500 m from the entrance of the mine. Rescue teams were dispatched to search for the trapped workers. Several boreholes were drilled to intersect the locations of the trapped miners but accuracy was a problem and the drill missed the targeted presumed locations of the trapped miners.	Several boreholes had to be drilled which resulted in a long-lasting SAR operation. SAR operations were hindered by additional collapses due to seismic activities causing further delays in the process of locating the trapped miners. The trapped miners were never found and later declared dead as the bodies were never recovered.

Table 13 (continued)

Mine	Country	Date of incident occurrence	Commodity mined	Depth at which accident occurred (m)	Mining method	Cause of accident	Area of occurrence	Number of trapped miners	Number of rescued miners	Number of fatalities	Duration of SAR operation (days)	Rescue attempt and causes of failed and prolonged rescue attempt	Key observations and learnings
Beaconsfield	Australia	25-Apr-06	Gold	925	Sub-level stoping	Fall of ground	Stope	3	2	1	14	A seismic event triggered a fall of ground inside the mine when 17 miners were working underground. The accident trapped 3 miners, while the other 14 managed to escape to a safe area. A SAR operation lasted for up to 14 days and located only two trapped miners. The rescue operation made use of a remote-controlled earth-mover to clear rock at the collapsed area.	The trapped miners survived for over two weeks underground from seeping groundwater from the collapsed rock. Not anyone could have managed to survive for 14 days without medical care, food and water. This was a special case and the survivors can be considered very lucky to have made it out alive under these uncongenial circumstances.
Sago	United States	02-Jan-06	Coal	85	Longwall	Gas explosion	Stope	13	1	12	2	A blast caused a ground collapse resulting in 13 miners trapped underground while 1 miner escaped. Two utility vehicles were transporting miners to the working areas when the accident occurred. The vehicle at the back managed to escape the explosion while the other vehicle had passed the point of the explosion. SAR was initiated to rescue the trapped miners using robotic vehicles were used to try and locate the trapped miners due to the risk of further explosions underground.	SAR operation were delayed due to high levels of methane and carbon dioxide, water seepages, explosive gas concentrations and unsafe roof conditions. The trapped miners tried to stay alive and made use of a system that was in place to signal their location. The rescue teams were also withdrawn from the search after nine hours due to a risk of further explosions.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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