Rock Mechanics and Rock Engineering
https://doi.org/10.1007/s00603-024-04045-8

ORIGINAL PAPER

Fuzzy Cognitive Map for Evaluating Critical Factors Causing Rockbursts in Underground Construction: A Fundamental Study

Shahab Hosseini[1] · Danial Jahed Armaghani[2] · Xuzhen He[2] · Biswajeet Pradhan[3] · Jian Zhou[4] · Daichao Sheng[2]

Received: 4 January 2024 / Accepted: 18 June 2024

Abstract

The rockburst phenomenon in excavation endeavours reveals a multitude of complexities and obstacles that significantly impact both the technical and financial dimensions of project execution. Investigating critical rockburst factors in underground excavations is of considerable importance for addressing pivotal safety issues and operational complexities within the field of underground excavation projects. This research proposes an innovative approach based on an expert-based fuzzy cognitive map (FCM) framework, aiming to identify and prioritize the key critical rockburst factors prevalent in underground excavations and tunnelling. A tailored cognitive map of the parameters of problem was constructed, integrating 56 critical and critical factors meticulously curated by a team of seasoned managers, engineers, deputy managers, trainee engineers and assistant managers. The structured cognitive map was meticulously developed, considering the relative weights of the identified critical factors and their intricate interrelationships—all informed by the invaluable insights and expertise of seasoned engineers in the field. Subsequently, the cognitive map underwent a systematic solution process, whereby the causal relationships and influences amongst the identified critical factors were analysed and factored in. The outcomes of the comprehensive analysis unveiled several critical factors: lack of rockburst risk assessments, high in situ stress, presence of rock seams and weak layers, rock quality variations, and geological heterogeneity as the most paramount concerns demanding immediate attention and strategic intervention. By adopting the proposed FCM approach and leveraging the collective expertise of industry professionals, this research offers a robust and systematic framework for comprehensively assessing and addressing the key challenges associated with rockburst events in underground excavations and tunnelling projects, thereby fostering enhanced project performance and efficacy within the field.

Highlights

- A comprehensive fuzzy cognitive map, based on industry professionals, emphasiSes 56 critical rockburst factors.
- In rockburst events, the created map considers factor weights, enabling systematic analysis and strategic intervention for project efficacy.
- Key concerns revealed include the absence of risk assessments, high in situ stress, rock seams, quality variations and geological heterogeneity.

✉ Danial Jahed Armaghani
danial.jahedarmaghani@uts.edu.au

Shahab Hosseini
h.seyyedshahab@modares.ac.ir

Xuzhen He
Xuzhen.He@uts.edu.au

Biswajeet Pradhan
Biswajeet.Pradhan@uts.edu.au

Jian Zhou
j.zhou@csu.edu.cn

Daichao Sheng
Daichao.Sheng@uts.edu.au

1 Department of Mining Engineering, Faculty of Engineering, Tarbiat Modares University, Tehran, Iran

2 School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia

3 Centre for Advanced Modelling and Geospatial Information Systems, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, Ultimo, NSW, Australia

4 School of Resources and Safety Engineering, Central South University, Changsha 410083, People's Republic of China

Published online: 04 July 2024

- Utilising fuzzy cognitive map and industry expertise provides a robust framework for addressing rockburst challenges in underground projects.

Keywords Rockburst · Fuzzy cognitive map · Underground excavations · Cause-and-effect relationship · Critical factors

1 Introduction

Rockburst is a significant and complex phenomenon that occurs in underground mining and tunnelling operations. It is characterised as a sudden occurrence of intense rock collapse, resulting from the release of stored elastic energy within a rock formation situated in a high-pressure subterranean setting (Cai 2013). Since the initial documentation of rockburst occurrence at the England Tin Mine in 1738, rockburst has gained acknowledgment as a foremost perilous geological hazard with significant implications (Xiating et al. 2013). Rockburst incidents may lead to the ejection of rock fragments, ground displacement, injuries to workers and engineers, and potential damage to mining infrastructure and equipment. Numerous mine and underground construction reports related to rockburst accidents exist globally, with 172 reports documented in the US during the period from 1936 to 1993. In addition, severe hazard incidents have been reported in the Jinping II Hydropower Station tunnel in China, as well as in South Africa (Potvin et al. 2000), Germany (Potvin et al. 2000), Peru (Wang and Zhang 2010), India (Wang and Zhang 2010), Japan (Wang and Zhang 2010), Australia (Qiu and Zhou 2023), Norway (Qiu and Zhou 2023), Canada (Qiu and Zhou 2023) and Switzerland (Qiu and Zhou 2023). Because of the intricate nature of rockburst and the myriad of factors that influence it, such as stress conditions, geological discontinuities, seismic activities and mining operations, minimising rockburst accidents is considered a long-term and unsolved challenge in the mining industry and underground constructions. Figure 1 depicts various types of rockbursts. As mining operations and underground constructions extend deeper and become more mechanised, the occurrence of rockbursts becomes more pronounced and presents greater challenges. Consequently, recognising the factors contributing to rockbursts and effectively controlling associated risks becomes more challenging. Therefore, ongoing research into prediction methods and technologies is vital to accurately assess destructive potential of rockburst accidents.

During the past decades, many attempts have been made to analyse rockburst events worldwide. Although these studies achieved good results and provided insights into predicting rockbursts, they fall short of achieving complete control over these indices. In terms of rockburst estimation, previous investigations have identified two categories of studies: long term and short term. Long-term estimation of rockbursts involves forecasting the occurrence and potential impacts of this geological phenomenon over extended periods. It entails making initial evaluations of the rockburst pattern during the initial phases of underground engineering. Various techniques have been employed for estimating long-term rockbursts, including empirical approaches, numerical simulations and intelligent models (Afraei et al. 2019; Qiu and Zhou 2023). During the testing phase of underground mining projects, empirical approaches, including single and multi-index metrics, are commonly utilised. Whilst these approaches are uncomplicated and easy to implement, their applicability is confined to specific environments, limiting their effectiveness. Numerical simulations have also been used for rockburst modelling and control (Fanjie et al. 2022). However, replicating rockburst motion is challenging due to input variable sensitivity and limitations of the modelling framework in capturing real rock behaviour. Short-term estimation of rockbursts involves predicting their occurrence in the immediate future. Short-term forecasting commonly relies on live monitoring systems, such as seismic sensors, stress metres and microseismic (MS) monitoring. These systems continuously gather information on the behaviour of rock masses and changes in stress within the excavation environment. Xue et al. (2020) examined variations in MS activity before and after rockburst incidents. They observed that sudden declines in the energy index, accompanied by rapid increases in cumulative apparent volume, acted as indicators signalling an impending rockburst event. Focusing on the Jinping II Hydropower Station in China, Feng et al. (2019a) utilised real-time MS monitoring data for forecasting rockbursts in specific sections of the deep headrace and tailrace tunnels. Their approach involved integrating real-time MS information with assessments of rockburst hazard levels, resulting in successful predictions and favourable outcomes. However, these monitoring systems are associated with some issues or concerns such as low accuracy of prediction due to complexity of geological structures, and false alarms due to difficulty distinguishing between benign and hazardous events (Feng et al. 2019a; Pu et al. 2019; Xue et al. 2020).

Determining whether there is excessive stress on the ground depends on comparing the stresses present in the surrounding ground near an opening to the ground's own strength (Palmström 1995). According to Palmström (1995), the rock mass index (RM_i) is a reliable measurement that may be used on continuous ground. It is a representation of

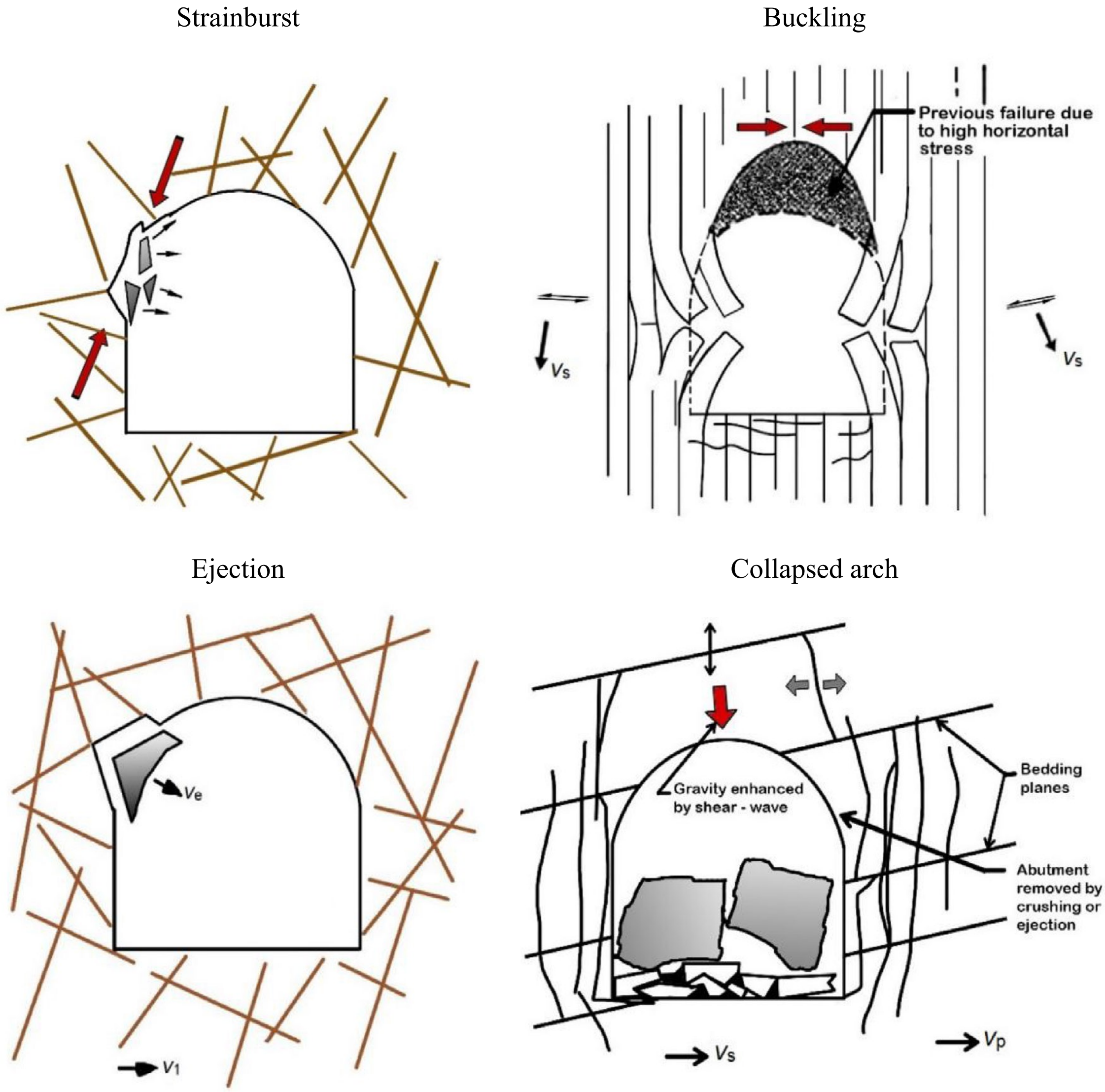
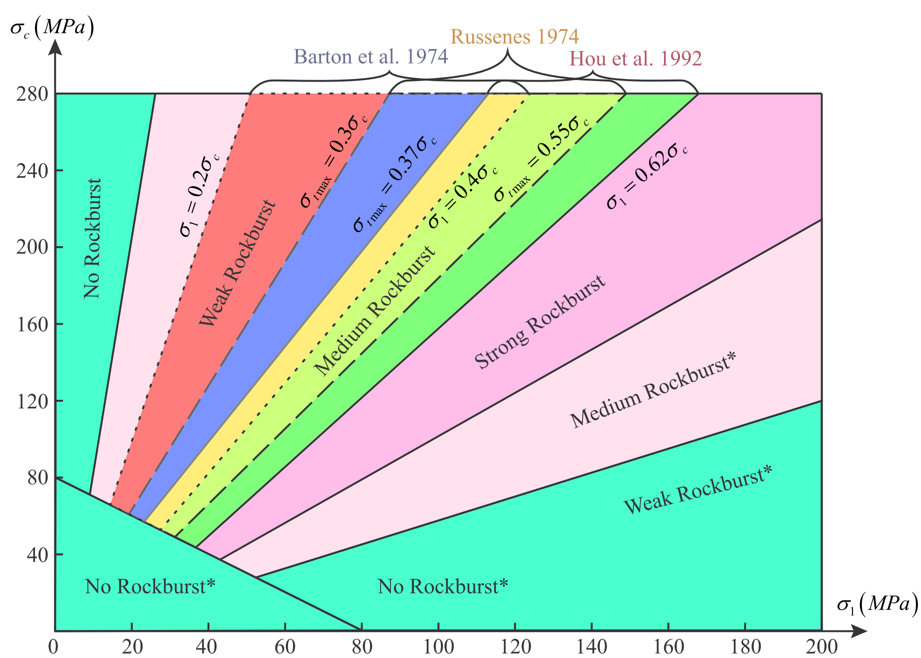


Fig. 1 Different type of rockburst phenomenon modified from Ortlepp and Stacey (1994)

the strength of the rock mass. The competency factor, which is represented by the equation $Cg = RM_i/\sigma_\theta$ can be evaluated with the help of this index. Based on Griffith's hypothesis and the tensile strength of rock, Peng et al. (1996) developed formulas for the critical stress of rockburst in underground apertures. These formulas were the result of their work. Utilising the ratio of compressive to tensile strengths is one method that can be utilised to describe rockburst. When σ_θ/σ_t is greater than or equal to 8, underground cavern rockbursts may occur—for small rock burst intensity, when σ_c/σ_t is low, and for lower intensity rock burst, when σ_c/σ_t is high. The ratio between uniaxial compressive strength (σ_c) and tensile strength (σ_t), denoted as σ_c/σ_t, serves as a crucial metric for delineating the mechanical properties of rock formations. Its significance becomes pronounced in the assessment of rock burst severity, where fluctuations in this ratio profoundly impact the likelihood of rock mass failure under varying stress regimes. When discussing minor instances of rock burst intensity, we are referring to situations where the scale of the event remains relatively limited. In such scenarios, the σ_c/σ_t ratio typically diminishes, indicating a heightened vulnerability of the rock mass to tensile failure as opposed to compressive failure. This heightened susceptibility stems from factors such as the presence of pre-existing fractures or structural discontinuities within the rock matrix. Similarly, occurrences of lower intensity rockburst events entail a moderate release of energy compared to larger scale phenomena. Under such circumstances, the σ_c/σ_t ratio tends to rise, signifying an augmented resilience of the rock mass against tensile failure vis-à-vis compressive failure. This enhanced resistance can be ascribed to factors such as the cohesive forces and interlocking mechanisms amongst intact rock grains, which collectively fortify the structural integrity of the rock mass.

The findings of a research project that was carried out by Russenes (1974) on rockbursting issues in tunnels that were situated along steep slopes in Norway led to the classification of rockbursting activity into four distinct categories, with the range of these categories being from 0 to 3. Whilst Class 0 indicates that there is no rockbursting, Class 3 indicates that there is high or violent rockbursting. Through the utilisation of finite element models and Kirsch's equation ($\sigma_{tan} = \sigma_{\theta max} = 3\sigma_1 - \sigma_3$), Russenes (1974) managed to determine the maximum tangential stress that was exerted on the edge of the tunnel. Subsequently, the stress was plotted against the strength values (Fig. 2). In their 1974a study, (Barton et al. (1974) and colleagues utilised the value of σ_c/σ_1 to make predictions regarding the likelihood for rockbursts under the Q geomechanical categorization system. Furthermore, Hou et al. (1992) conducted an investigation to determine the value of σ_c/σ_1 to forecast the likelihood for rockburst. They compared their findings with the research conducted by Russenes (1974) and Barton et al. (1974). On the other hand, these criteria only took into account the stress conditions of the rock that was around the area, missing out on important lithological issues.

Studying critical rockburst factors holds substantial significance in addressing critical safety concerns and operational challenges in the domain of underground excavations. Since the inception of humanity on Earth, humans have relied on resources and minerals as essential means of sustenance and survival. With the advent of the Industrial Revolution during the nineteenth century, there has been a gradual escalation in the exploitation pattern, with surface minerals being depleted, prompting a shift towards deeper exploration. In contemporary society, mining depths exceeding 1,000 m have become commonplace. China, for example, boasts more than 47 coal mines surpassing this depth threshold. Similarly, since the 1980s, coal mines exceeding 1,000 m have emerged in Britain, Japan, Germany and Poland. Before 1996, over 80 metal mines in the United States, Canada, Australia, India, South Africa and Russia had been drilled beyond the 1,000-m mark. Furthermore, in Europe, sub-alpine base tunnels wider than 10 m are being constructed at depths exceeding 2 kms. In the realm of nonferrous metal mining, operations have delved even deeper, reaching depths of 4,000 m and beyond, exemplified by mines such as the Mponeng and TauTona (or Western Deep Level) gold mines in South Africa. In Australia, the Gwalia gold mine near Leonora holds the record as the deepest mine, extending beyond 2 kms in depth (Mahmoud 2023). With the escalating demand for mineral resources leading to deeper and more complex underground operations, the risk of rockbursts poses a significant threat to the safety of engineers/workers and the stability of underground infrastructure (Ribeiro e Sousa et al. 2017). By adopting a systematic and quantitative approach, this research seeks to unravel the intricate web of geological, geomechanical and operational parameters that influence rockburst susceptibility. This not only encompasses traditional factors such as rock strength, stress conditions, and seismicity but also delves into less explored variables, including mining-induced stresses, structural discontinuities and dynamic changes in geological formations over time.



(a)

Fig. 2 Rockburst phenomenon as a function of the maximum tangential stress in an underground excavations and the compressive strength of the rock mass modified from Russenes (1974), Hou et al. (1992), and Zhou et al. (2018)

The identification and analysis of the critical factors, along with the elucidation of their interconnectedness through FCM methodology, provide a foundational understanding of the complexities surrounding rockburst occurrences. The study's contributions extend beyond mere comprehension, as it offers tangible benefits for industry practices. Decision-makers in geotechnical engineering can utilize the findings of this research to have safer practices and enhance overall operational risk management. Having a practical framework for guiding the industry towards safer and more resilient underground excavation practices is essential for any underground excavation project.

This paper addresses a significant gap in the existing literature by comprehensively evaluating and prioritizing rockburst factors in underground construction. Previous studies have primarily focused on identifying individual factors contributing to rockbursts, such as geological-, geomechanical- and mining-related factors. However, there remains a notable gap in the literature regarding the integration of advanced methodologies, such as Fuzzy Cognitive Maps (FCMs), to facilitate a holistic and dynamic assessment of the complex interdependencies amongst these factors. FCMs offer a more nuanced understanding of the causal relationships and system dynamics governing rockburst occurrences. The main motivation for using the FCM method is to address the applying different correlated factors. This method is used only when several factors affect each other. Some of the main advantages offered by the FCM technique include: (i) Taking into account causality relationships amongst system concepts, (ii) streamlining complex decision-making processes, (iii) minimizing reliance on expert opinions and enhancing weight accuracy through learning algorithms and (iv) decreasing computational time. The insights gained from this research will not only enhance overall safety standards and risk management protocols in underground constructions/excavations but also foster a more comprehensive understanding of the intricate dynamics governing rockburst occurrences. The outcomes of this study have the potential to significantly influence policy development, safety regulations and operational practices, thereby contributing to the sustainable and efficient development of underground constructions/excavations globally.

2 Materials and Methods

2.1 Identification of Critical Rockburst Factors

To discuss factors contributing to rockbursts, it is necessary to establish a widely accepted definition for the term "rockburst". Ortlepp (2005) highlights the absence of a universally recognised definition for a rockburst, although numerous journal articles have attempted to describe it. For the purpose of describing the occurrence of a rockburst, a number of different governmental agencies and researchers have supplied definitions (Kaiser et al. 1996; Blake and Hedley 2003). A temporal overview of rockbursts is presented in Fig. 3, which is based on a comprehensive review that spans from 1965 to 2018. This review contains many definitions of rockbursts that are based on the suggestions made by the researchers (Cook 1965; Obert and Duvall 1967; Thrush 1968; Blake 1972; Zhen-Yu 1988; Gill et al. 1993; Ortlepp 1997; Singh and Goel 1999; Wang et al. 1999; Guo and Yu 2002; Blake and Hedley 2003; He 2005; Solak 2009; Li 2014; Zhou et al. 2017, 2018; Feng et al. 2019b; Zhao et al. 2020; Farhadian 2021).

Taking into consideration the numerous definitions that are shown in Fig. 3, it is possible to draw the conclusion that there is currently no definition of a rockburst that is universally acknowledged. In certain definitions, particular terms are given more weight than others. Some examples of these phrases include "violent failure," "highly stressed brittle rock," and "strain energy." These include the detachment of small rock fragments and seismic events that move significant volumes of rock, much like a local earthquake. Both of these examples are examples of these types of phenomena. These events encompass a wide spectrum of occurrences. Other definitions emphasize the destructive aspects associated with rockbursts. The quick release of energy that is accompanied by microseismic occurrences in the early phases of a rockburst is what Cook (1965) uses to characterise a rockbump. According to Russenes (1974), a rockburst can be defined as any event that involves some combination of noises, wall collapsing, spalling, and even ejection and new fracture faces. According to Tan (1988), the only failures that should be categorized as rockbursts are those that result in rock ejection. Fractures that do not result in dynamic ejection are defined as static brittle failures. In the context of destructive events, it is possible that a form of rockburst might be induced by compression and tensile tests, biaxial loading and unloading tests, and triaxial loading and unloading testing. A rockburst is defined not by the nature of the burst event itself but rather by the damage that is caused by the burst, as stated by Kaiser et al. (1992). A great number of theories have been suggested to examine the localisation of deformation in rockburst failure and the stability of rock mechanical systems (He 2005; Wang et al. 2009; Gao 2010; Li et al. 2011).

A complete investigation into the various components contributing to rockbursts in tunnelling operations is necessary to identify the factors causing rockbursts in underground construction. Rockbursts are sudden and violent failures of the rock mass surrounding underground openings, and they pose significant safety risks to workers and the stability of the excavations (DOU et al. 2009; Evariste Murwanashyaka 2019). Understanding and identifying the factors

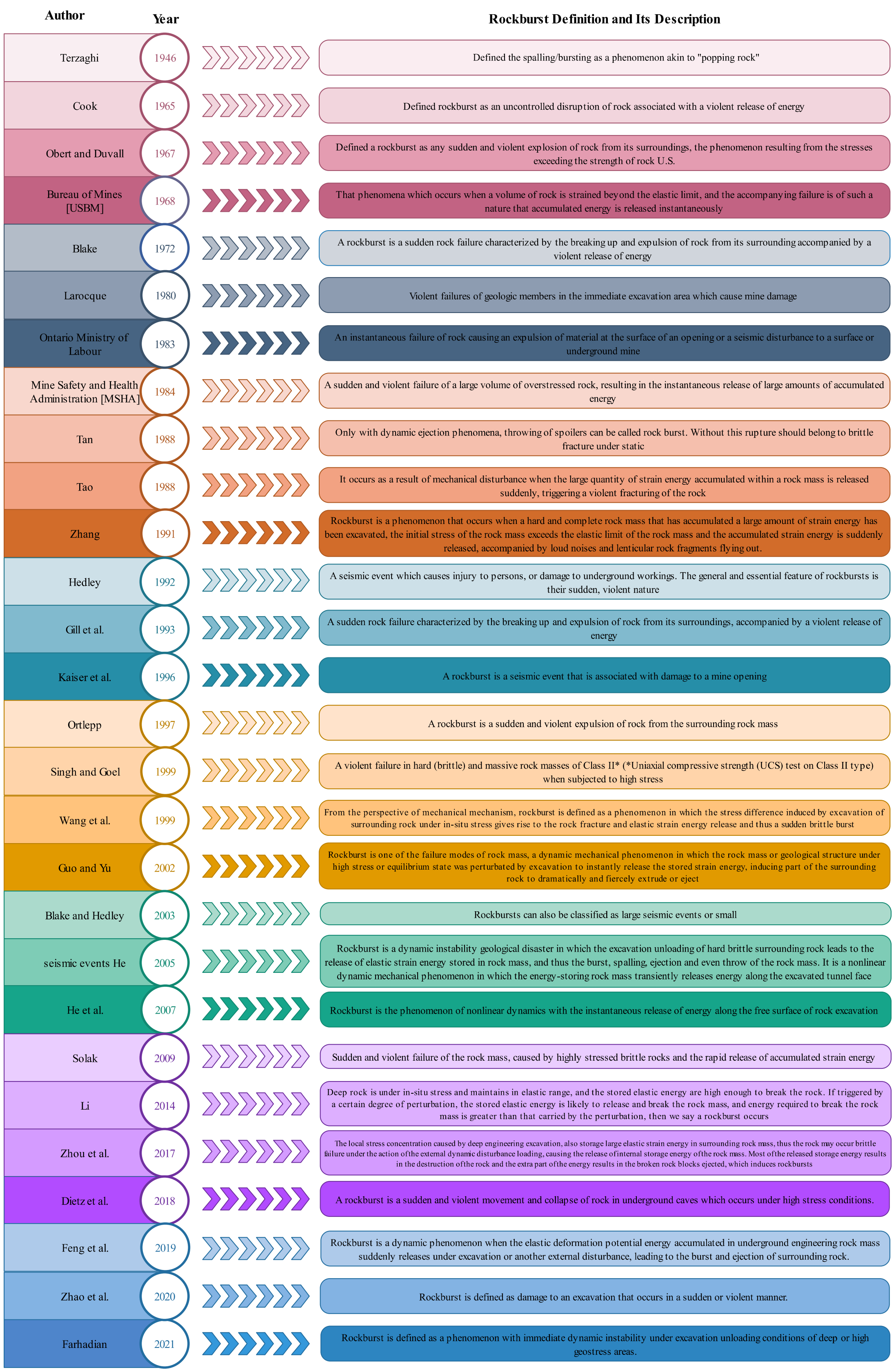


Fig. 3 Chronological progression of rockburst definitions from 1946 to 2021

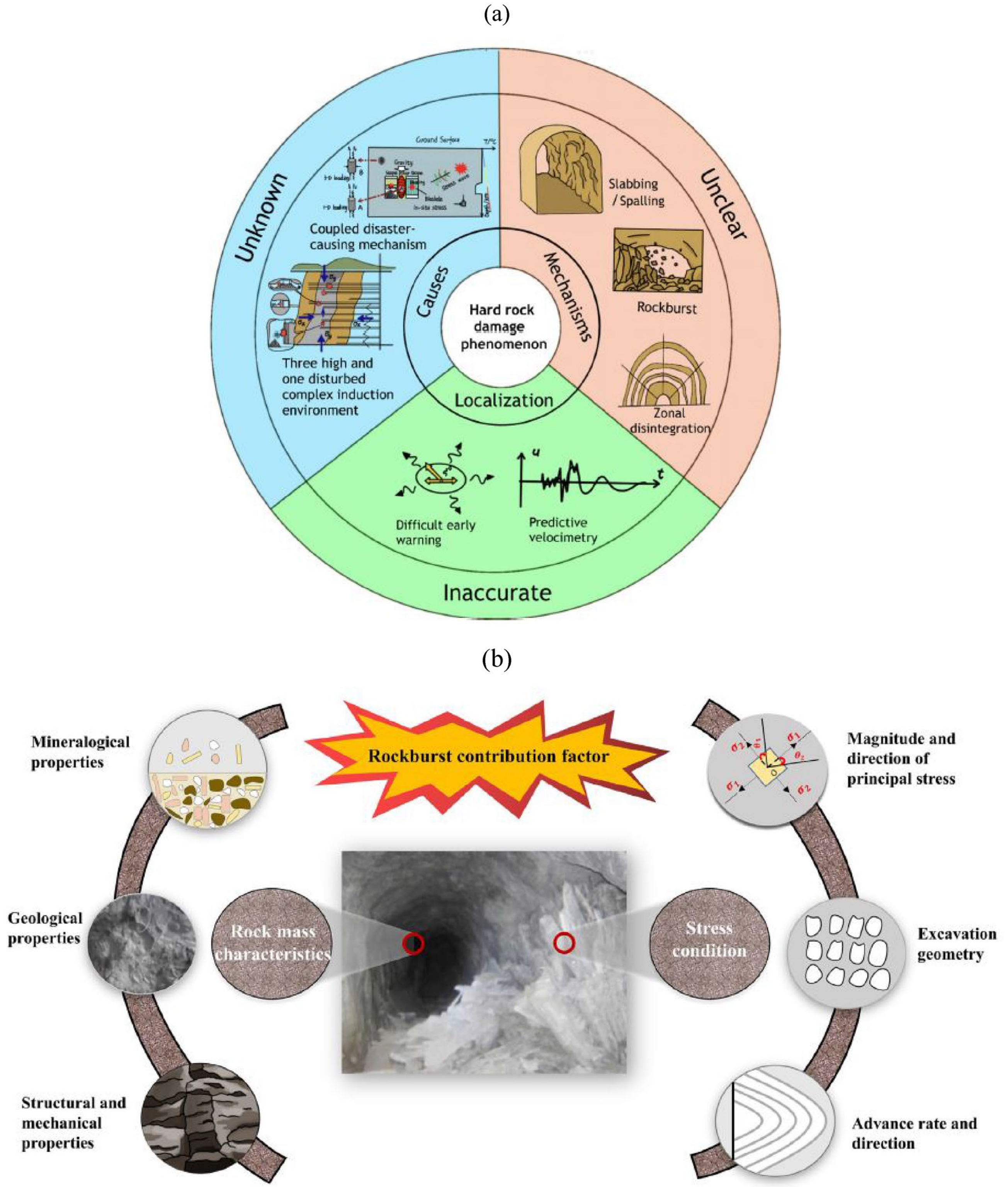


Fig. 4 **a** The situation of underground excavations adapted from Zhou et al. (2024) and **b** effective parameters on rockburst in underground excavations based on Zhou et al. (2024)

that trigger rockbursts is essential for preventing these hazardous events. The situation of underground excavations and the particular considerations relevant to rockburst are shown in Fig. 4. The establishment of a general technical theory of rockburst mechanisms, especially with respect to fault slip bursts, has proven to be difficult due to the large number of important components that contribute to rockbursts. As a result, additional investigation is required to shed light on this topic. These difficulties are inextricably associated with the nature of the deep technological field. Therefore, it is of the utmost importance to give serious consideration to the choice of prediction and preventive technologies based on the engineering geological characteristics of the rock mass.

Here is a step-by-step explanation of how to determine critical rockburst factors in underground excavations:

The first step involves collecting extensive data on the geological, geotechnical and mining conditions of the underground construction/excavation. This data may include information on rock types, stress levels, seismic activity and historical records of rockbursts. Hence, it is advisable to integrate comprehensive laboratory and field analyses to identify crack initiation, serving as an indicator of in situ explosion-like fractures. These approaches may encompass: (i) Methods rooted in stress–strain relationships (such as the volumetric strain method, lateral strain method, extensional strain method, TLSR, crack volumetric strain method, etc.), (ii) stress-oriented approaches (including the modified Griffith and Hoek–Brown criterion under triaxial loading conditions) and (iii) techniques reliant on instrumentation (such as electrical resistivity, optical diffraction patterns, laser speckle interferometry, ultrasonic probing, digital image processing methods and acoustic emission (AE) techniques) (Mutaz et al. 2024).

- Geological assessment: A geological assessment is conducted to understand the properties and characteristics of the surrounding rock. This includes assessing rock type, structure, fault lines, and the presence of any geological anomalies.
- Geotechnical analysis: To analyse the mechanical qualities of the rock mass, such as its strength, deformation behaviour and stress distribution, geotechnical investigations are very necessary. This information helps in assessing the stability of the excavation.
- Stress and strain analysis: A thorough analysis of the stress and strain conditions within the rock mass is conducted to identify areas of high stress concentration. Stress concentrations are a common trigger for rockbursts.
- Seismic monitoring: Continuous monitoring of seismic activity in the area is essential. Seismic events and their magnitude can provide early warning signs of potential rock bursts.
- Numerical modelling: Numerical modelling, using computer simulations, helps in predicting potential areas of rock burst initiation. These models consider factors like stress distribution, geological features, and the mechanical behaviour of the rock mass.
- Historical analysis: A review of historical records and incidents of rock bursts in the area is essential to identify patterns and potential causes.
- Identification of triggering factors: The collected data and analyses help in identifying specific factors that trigger rock bursts. These may include high stress concentrations, geological anomalies, seismic events or a combination of these.
- Risk assessment: Once the critical factors are identified, a risk assessment is carried out to evaluate the likelihood and consequences of rock bursts in different parts of the excavation.
- Preventive measures: Based on the identified critical factors, appropriate preventive measures are implemented. These measures can include ground support systems, stress-relief techniques, altered mining methods, or improved monitoring and warning systems.
- Continuous monitoring: Continuous monitoring of the excavation is essential to track changes in the underground conditions and the effectiveness of preventive measures. Adjustments may be made as needed.
- Emergency response planning: An emergency response plan is developed to ensure the safety of workers in case a rockburst occurs despite preventive measures.

By systematically assessing and addressing the critical rockburst factors, underground construction/excavation projects can be made safer for workers and the overall integrity of the excavations can be preserved. This process requires a multidisciplinary approach, involving geologists, geotechnical engineers, and mining experts, to effectively mitigate the risks associated with rockbursts.

Critical rockburst factors in underground excavations pertain to conditions and circumstances that result in sudden and violent failures of the surrounding rock mass. These factors encompass a complex interplay of geological, geotechnical and operational elements. High stress levels within the rock, often aggravated by deeper excavations, increase the risk of rockbursts. Geological faults and the type of rock being excavated can introduce zones of weakness, making the rock mass susceptible to failure. Seismic activity, induced by nearby events, can exacerbate stress changes. The choice of excavation methods, especially those involving high-impact activities, can escalate stress and strain concentrations. Furthermore, inadequate ground support systems and the presence of groundwater can significantly influence the potential for rockbursts. Past incidents of rockbursts in the area serve as crucial indicators, and it is imperative to comprehensively identify, analyse and mitigate these critical factors to ensure the safety and stability of underground excavations.

Several factors can contribute to the occurrence of rockbursts in underground excavations, and these can be broadly categorised into geological, geomechanical and mining-related factors.

- Geological factors:
- Rock type and properties: The type of rock being excavated plays a crucial role in the occurrence of rock bursts. Rocks with high strength and brittleness are more prone to sudden failure and can trigger rock bursts.
- Geological structures: The presence of geological structures such as faults, joints and fractures can create stress concentrations and weak zones that may lead to sudden failure and rockbursts.
- Rock stress: High in situ stresses in the surrounding rock mass can accumulate over time and eventually exceed the rock strength, leading to sudden failure and rock bursts.
- Geomechanical factors:
- Rock mass quality: Poor rock mass quality, characterised by high levels of jointing, fracturing and weathering, can increase the likelihood of rock bursts.
- Rock support effectiveness: Inadequate or ineffective rock support systems can lead to unstable excavations, thereby increasing the risk of rockbursts.
- Groundwater pressure: High groundwater pressure can weaken the rock mass and increase the risk of sudden failure and rock bursts.
- Mining-related factors:
- Mining-induced stress changes: Excavation activities can alter the stress distribution in the surrounding rock mass, leading to stress concentrations and potential rock bursts.
- Mining depth: Deeper excavations often encounter higher in situ stresses, which can contribute to the occurrence of rock bursts.
- Mining method: Certain mining methods, such as longwall mining and deep drilling, can induce high stress concentrations and increase the likelihood of rock bursts.

Various methods of excavation, including drill and blast, tunnel boring machines (TBMs), or mechanical excavation, may produce different impacts on the stability of the surrounding rock formation. For instance, mechanical excavation techniques might cause less disturbance and stress compared to conventional drill and blast methods, potentially decreasing the likelihood of rock bursts. The manner and magnitude of blasting can exert a significant influence on the stability of the nearby rock structure. Incorrect blasting practices or excessive use of explosives have the potential to generate elevated stress levels and initiate fractures within the rock mass, thereby elevating the risk of rock bursts. The order in which various segments of the excavation are unearthed can influence the distribution of stress within the rock formation. If the excavation proceeds in a manner that results in significant differential stresses between neighbouring areas, it may heighten the susceptibility to rock bursts. Thus, the method employed for rock excavation can impact the occurrence of rock bursts by affecting stress distribution, the stability of the rock mass, and the effectiveness of support systems. Consequently, it is imperative to choose an appropriate excavation method and implement robust support measures to mitigate the risk of rock bursts in subterranean excavations. Accordingly, several related factors to the construction method of rock excavation were considered such as uncontrolled blasting effects, blast-induced vibrations, inadequate perimeter blasting, blasting sequence and timing, poor drilling and blasting practices, inadequate blast design, and stress redistribution during blasting.

To mitigate the risk of rockbursts, several measures can be implemented, including the use of appropriate rock support systems, pre-excavation stress mapping, regular monitoring of stress changes, and the implementation of engineering controls to manage and relieve stress concentrations. In addition, proper geological investigations and geomechanical assessments can help in identifying potential risk factors and developing effective strategies for preventing and managing rock bursts in underground excavations.

The key personnel and stakeholders involved in underground excavation fields were specified and chosen for participation, whilst in-depth discussions were held with the engineers and project executives.

Some localized issues pertaining to tunnel excavations through drilling and blasting were found and subsequently excluded from consideration. This study specifically targeted critical challenges prevalent across a majority of completed projects. Initially, a comprehensive list of 89 critical factors associated with rockburst was compiled. Subsequently, following consultations with industry experts, 56 of the most significant factors, distinguished by their high occurrence rate and consequential impact, were selected for comprehensive evaluation and scrutiny (refer to Table 1). Other factors were omitted from the study due to their infrequent occurrence and limited impact on underground excavations.

2.2 Fuzzy Cognitive Map Theory

A FCM is a computational model that represents and simulates complex systems, particularly useful in fields such as decision support systems. In the context of FCMs, a cognitive map refers to a graphical representation of knowledge about a system. The cognitive map is constructed using a network of nodes interconnected by directional arrows that denote causal relationships amongst various elements (Axelrod 2015). Kosko (1986) introduced the FCM as a visual

Table 1 Critical rockburst factors in the underground excavations considered in this study

Category	Factor	
Operational factors	A1	Poor water management
	A2	Uncontrolled blasting effects
	A3	Inadequate post-grouting
	A4	Blast-induced vibrations
	A5	Inadequate perimeter blasting
	A6	Inadequate geological mapping
	A7	Inadequate energy control
	A8	Inadequate monitoring of tunnel behaviour
	A9	Lack of ventilation and gas control
	A10	Blasting sequence and timing
	A11	Vibration damage from nearby activities
	A12	Lack of ground stress management
	A13	Poor drilling and blasting practices
	A14	Lack of pre-grouting
	A15	Excessive explosive charges
	A16	Lack of in situ stress measurements
Geological factors	A17	Presence of geological structures (e.g., joints and fractures)
	A18	Presence of rock seams and weak layers
	A19	Geological anomalies
	A20	High in situ stress
	A21	Geological fault zones
	A22	Rock quality variations
	A23	High rockburst-prone rock types (e.g., high quartz content)
	A24	Geological heterogeneity
Safety and preparedness factors	A25	Lack of personal protective equipment (PPE)
	A26	Neglecting safety culture
	A27	Lack of rockburst risk assessments
	A28	Inadequate pillar design and extraction plans
	A29	Insufficient ground support inspections
	A30	Lack of adequate training for personnel
	A31	Inadequate risk mitigation measures
	A32	Inadequate emergency response plans
	A33	Neglecting microseismic monitoring
	A34	Poor communication and warning systems
	A35	Inadequate safety regulations and enforcement
	A36	Lack of geophysical monitoring
	A37	Poor hazard identification and reporting
Engineering factors	A38	Inadequate rock mass characterisation
	A39	Tunnel geometry and design
	A40	Inadequate blast design
	A41	Inadequate ground support systems
	A42	Tunnel orientation and alignment
	A43	Weak tunnel lining materials
	A44	Unsupported or inadequately reinforced tunnel faces
	A45	High excavation rates
	A46	Improper drilling techniques
	A47	Excessive tunnel spans
	A48	Inadequate rock reinforcement
	A49	Excessive overbreak

Table 1 (continued)

Category	Factor	
Seismic and dynamic factors	A50	Amplification of ground motion
	A51	Induced seismicity
	A52	Stress redistribution during blasting
	A53	Inadequate monitoring: failing to implement real-time monitoring systems for stress, deformation, seismic activity, or gas emissions
	A54	Sudden energy release
	A55	Rock mass response to dynamic loading
	A56	Dynamic loading near geological structures

representation that elucidates these cause-and-effect connections amongst the elements.

The FCM comprises a collection of nodes, denoted as concepts (abbreviated as C_i), representing the conceptual components of the system. These concepts are linked together through weighted arcs, where each connection between two concepts C_i and C_j is assigned a weight denoted as W_{ij}. This weight signifies the degree of causality and characterises the nature of the relationship between the concepts (Bakhtavar et al. 2021; Hosseini et al. 2022b, 2023). When W_{ij} is greater than zero, it signifies a positive cause-and-effect relationship, whilst W_{ij} less than zero represents a negative causal connection. Conversely, when W_{ij} equals zero, it indicates an absence of a connection between the concepts. Subsequent to the graphical construction of the cognitive map, mathematical formulas are employed to analyse the model (Hosseini et al. 2022a, c). Following the identification of the values that are associated with a specific node, Eq. (1) is next utilised to ascertain the values of additional nodes that are connected to that particular node.

$$A_1(t+1) = f\left(A_1(t)\right) \sum_{i=1, j\neq i}^{n} \left(W_{ij} \cdot A_i^t\right) \quad (1)$$

where $A_I(t+1)$ indicates the value of the C_i concept at time $t+1$, and $A_I(t)$ denoting the value of the C_i concept at time t. W_{ij} signifies the weight assigned to the relationships between the C_i and C_j concepts. Besides, there is the function $f(x)$, which serves as a normalization function. Generally, the rewritten form of Eq. 1 is provided as Eq. (2):

$$A_{\text{new}} = f\left(A_{\text{old}} \cdot W\right) + A_{\text{old}} \quad (2)$$

In Eq. 2, we introduce A, which is a vector with dimensions $N \times 1$, often referred to as the concept value matrix. This vector encapsulates the values associated with each concept at any given time. Furthermore, we have the matrix W, sized $N \times N$, that represents the interconnections between the concepts within the system, along with the inclusion of the normalization function denoted as f.

When the result of multiplying two matrices exceeds predetermined threshold values for variables, the resultant values are associated with predefined limits. Consequently, each numerical value carries its unique definition and significance within the framework. The computations for FCM persist until one of the following conditions is met:

- The system reaches a steady state, indicated by the equality or minimal difference between A_{new} and A_{old}.
- The system exhibits chaotic behaviour.
- The desired number of iterations is attained.

A general topology of the cognitive maps is depicted in Fig. 5.

As depicted in Fig. 5, the element C_i serves as a representation of concepts, each forming a node within the network. These concepts are linked through arcs, their connections carrying assigned weights. The variable W_{ij} specifically characterises the cause-and-effect dynamics between C_i and C_j. When W_{ij} is greater than zero, it signifies a positive

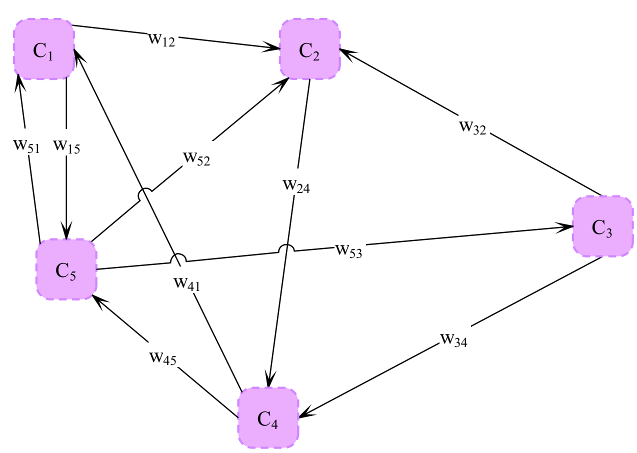


Fig. 5 A topology of the cognitive map

causal relationship, whereas a value less than zero, $W_{ij} < 0$, denotes a negative cause-and-effect association. Moreover, when W_{ij} equals zero, it signifies a complete absence of any relational connection between the interconnected concepts.

2.3 Experts and Their Knowledge

The consolidation of linguistic data concerning fundamental occurrences, collected from a panel of eight experts, is performed by taking into account their respective categorization and the associated significance. Notably, the experts may express varying degrees of opinion on a given attribute. The determination of their significance is based on diverse criteria, including their distinct professional positions, sector-specific experience, and educational attainment, as shown in Table 2.

Table 2 Score table to specify the importance level of the experts

Configuration	Class	Weightage score
Professional position	Manager	5
	Deputy manager	4
	Assistant manager	3
	Engineer	2
	Trainee engineer	1
Sectoral experience	≥ 13 years	5
	10–12 years	4
	7–9 years	3
	4—6 years	2
	≤ 3 years	1
Educational level	Professional degrees	5
	Doctoral degrees	4
	Master's degree	3
	Bachelor degree	2
	Associate degree	1

Table 2 provides a scoring system to determine the significance level of the experts involved in the research, with a focus on their qualifications, professional experience, and educational background. The table consists of three key parameters: Professional Position, Sectoral Experience, and Educational Level, each of which is assigned a weightage factor based on the importance associated with different categories within these parameters.

Sectoral experience evaluates the number of years of experience possessed by the experts within the specific sector relevant to the research. The weightage factors range from 5 for those with 13 or more years of experience to 1 for individuals with 3 or fewer years of experience. This evaluation recognises the significance of in-depth industry experience in providing valuable insights and informed opinions.

Educational level assesses the academic qualifications of the experts, considering their attainment levels, from associate degrees to professional degrees, each assigned a weightage factor from 5 to 1. This aspect recognises the influence of educational background in shaping the analytical capabilities, critical thinking and domain-specific knowledge of the experts.

By utilising this scoring system, researchers can objectively assess and assign appropriate weights to the opinions and contributions of the experts involved in the research process. This analysis ensures that the insights provided by the experts are evaluated within the context of their professional standing, industry experience, and educational qualifications, thereby enhancing the credibility and reliability of the research findings and recommendations. This scoring system facilitates a systematic and structured approach to incorporating expert opinions and expertise, thus contributing to the overall robustness and rigor of the research methodology.

In addition, Table 3 provides a comprehensive breakdown of the information that pertains to the panel of eight experts and the levels of significance that each of them possesses specifically. The purpose of the complete score table that is presented in Table 3 is to determine the level of significance

Table 3 Position, experience and education of the experts and their scores

Expert	Position	WFP	Experience	WFEx	Education	WFEd	Total score	Weight
Ex1	Manager	5	17 years	5	ME mining	5	15	0.158
Ex2	Manager	5	12 years	4	ME mining	5	14	0.147
Ex3	Engineer	2	3 years	1	BE mining	4	7	0.074
Ex4	Deputy manager	4	10 years	4	ME mining	5	13	0.137
Ex5	Trainee engineer	1	5 years	2	ME mining	5	8	0.084
Ex6	Assistant manager	3	9 years	3	ME mining	5	11	0.116
Ex7	Deputy manager	4	20 years	5	ME mining	5	14	0.147
Ex8	Assistant manager	3	14 years	5	ME mining	5	13	0.137

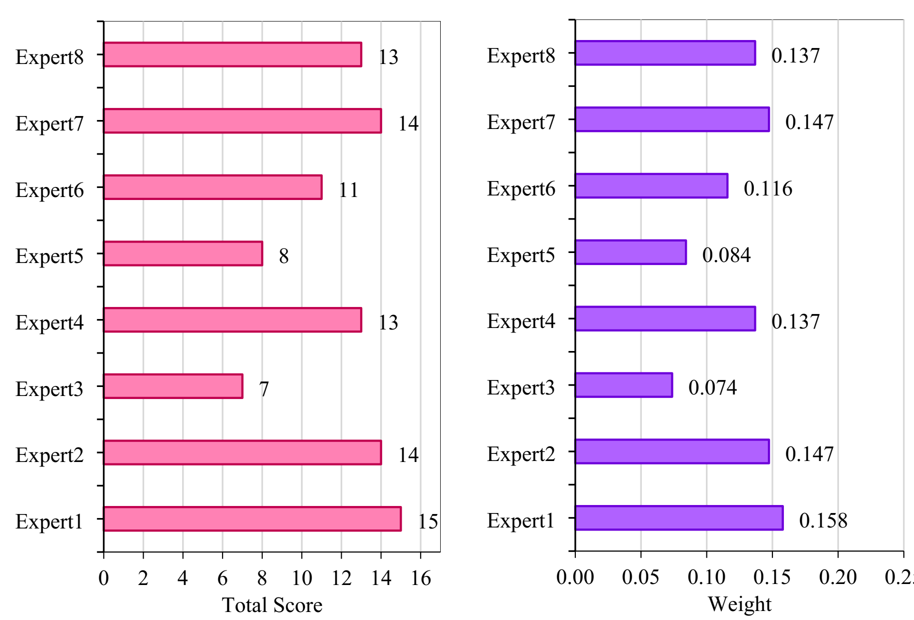
WFF: weighting factor of position, WFEx: weighting factor of experience, WFEd: weighting factor of education that each of the numerous experts who participated in the research hold. The table incorporates key factors such as the experts' position within the organization, their years of experience in the field, and their educational qualifications, each assigned a specific weightage factor. These weightage factors serve as a quantitative measure of the significance attributed to each of the parameters. The "Position" column in the table outlines the diverse hierarchical roles held by the experts, ranging from Manager, Deputy Manager, and Assistant Manager to Engineer and Trainee Engineer, each assigned a corresponding weightage factor based on their level of seniority and decision-making authority within the organization. The "Experience" column provides insights into the number of years each expert has spent in the relevant field, with weightage factors assigned based on the cumulative years of experience, thereby acknowledging the significance of extensive practical knowledge and industry-specific expertise. The "Education" column highlights the educational background of each expert, with weightage factors assigned to different degrees, such as ME Mining (Master's in Mining Engineering), BE Mining (Bachelor's in Mining Engineering), and others. This assessment recognises the influence of academic qualifications in shaping the analytical capabilities and domain-specific knowledge of the experts. The "Total Score" column represents the cumulative weightage assigned to each expert based on their position, experience and education, providing an aggregate measure of their overall importance level within the context of the research. The "Weight" column denotes the calculated score obtained by dividing the "Total Score" by the total possible weight as formulated in Eq. (3), offering a normalized measure to compare the relative importance levels of the different experts. This scoring mechanism enables a comprehensive and objective evaluation of the contributions and opinions provided by each expert, thereby enhancing the credibility and reliability of the research findings and recommendations. The results indicated that the highest and lowest weights are relevant to Expert1 and Expert3, respectively. Therefore, Expert1 is the one who has more experience and a higher level of education with better position. However, Expert3 has less experience and less knowledge. The assigned weights for experts and their scores are depicted in Fig. 6.

$$W_i = \frac{S_i}{\sum_{i=1}^{n} S_i} \tag{3}$$

2.4 Defining an FCM Framework for Rockburst Problem

The design of an FCM involves a systematic process that incorporates various steps to construct a graphical representation of a complex system. This cognitive mapping technique is widely used to model the causal relationships and interactions between different variables within a system. Here is an explanation of the key steps involved in the design of an FCM. The first step involves identifying the key variables or concepts that are relevant to the system under study. These variables represent the components of the system that have a causal influence on each other. Once the variables are identified, the next step is to define the relationships and interactions between these variables. These relationships can be positive, negative or neutral, indicating how the changes in one variable affect the others. The

Fig. 6 Assigned weights for experts and their score



FCM is typically represented as a directed graph, with nodes representing the identified variables and edges representing the causal relationships between the variables. The weights assigned to the edges typically indicate the strength and direction of the connections. The concepts or variables in the FCM are often represented using fuzzy logic, allowing for the consideration of imprecise or uncertain information. Fuzzy sets are used to capture the degrees of membership or influence of a variable on others, enabling a more flexible and nuanced representation of the system's dynamics. Once the FCM is constructed, it is evaluated and analysed to understand the behaviour and dynamics of the system. Simulation and analysis techniques can be employed to examine the propagation of influence and the overall behaviour of the system under different conditions and scenarios. The FCM design process often involves iterative refinement, where the model is updated and modified based on feedback from domain experts, empirical data, and observations from the real-world system. This iterative refinement helps improve the accuracy and effectiveness of the FCM in capturing the complexities of the underlying system.

Achieving optimal results in designing the desired FCM necessitates a combination of comprehensive knowledge, substantial experience and precise scripting. As a result, it is crucial to conduct a comprehensive analysis of the system that is being reviewed, to identify the variables that are responsible for the effects, and to enlist the assistance of a team of knowledgeable individuals. In the context of this study focused on devising an FCM for assessing the interplay of critical rockburst factors in underground excavations, the following sequential procedures have been undertaken:

- Identification of key system components and their interrelationships.
- The evaluation of connections and constituents on the basis of empirical experiences, field research, and the judgments of individuals with expertise.
- Selection of an appropriate method for computing the extent functions.
- The determination of the permissiveness of each and every component (node) with relation to the other components.
- Computation of the resultant effects amongst the components.
- Iterative repetition of this process until meeting the predetermined conditions.

The research employs the model proposed by Rodriguez-Repiso et al. (2007) to accomplish its main objectives. The model consists of four primary matrices: the Initial Matrix of Success (IMS), the Fuzzified Matrix of Success (FZMS), the Strength of Relationship Matrix of Success (SRMS) and the Final Matrix of Success (FMS). As highlighted in previous literature (Papageorgiou and Kannappan 2012; Hosseini et al. 2022b), noteworthy aspects include:

- Vigilance against potential misleading data within the completed SRMS.
- Recognition of factors that might lack relevance to the matrix, thereby lacking causal relationships.
- Necessity for expert insights in data analysis and the transformation of SRMS into FMS.
- Identification of random linkages between two vectors during SRMS data analysis.

By following these steps, researchers can create a comprehensive and effective FCM that provides valuable insights into the causal relationships and dynamics of complex systems, such as those encountered in various scientific, engineering and social domains.

2.4.1 The Initial Matrix of Success for the Rockburst Phenomenon

The Initial Matrix of Success (IMS) is a matrix that has the structure of a $n*m$ matrix. Here, n indicates the number of concepts or variables, and m represents the number of experts or individuals that were surveyed to collect data. Within the matrix, each element (q_{ij}) denotes the level of significance attributed by individual j to concept i, based on a predefined scale. Due to the subsequent transformation of data into a fuzzy set with a range of zero to one, this scale can vary across various projects and even for different success criteria within the same project (Rodriguez-Repiso et al. 2007).

In the context of the present study, Table 4 embodies the initial matrix addressing the core issue, with only 10 out of the total 56 factors identified and correspondingly featured in the rows of the matrix. The suggestions by each of the eight specialists are shown in the columns of the matrix, together with the scores that they have allocated to each factor. Following the creation of the IMS, an assessment of each factor's effectiveness is conducted, as depicted in the tabulated results provided in Table 5.

2.4.2 The FZMS for the Rockburst Phenomenon

The numerical vectors of V_i are converted into fuzzy sets, where each factor indicates the level of correlation between component q_{ij} and the V_i vector. This transformation takes place after the V_i vectors have been transformed. This conversion process, as outlined by previous research (Papageorgiou and Kannappan 2012; Hosseini et al. 2022b), involves the following steps: (1) identification of the maximum value for V_i and (2) assignment of $X_i = 1$ for the maximum value, employing Eq. (4).

Table 4 A summary of the IMS relevant to the critical rockburst factors

The IMS								
Rockburst factor	Expert							
	1	2	3	4	5	6	7	8
A1	85	90	95	70	90	95	85	70
A2	70	75	80	80	100	100	80	70
A3	75	100	65	15	85	70	70	25
A4	85	65	100	90	100	100	100	75
A5	70	95	70	70	80	100	70	90
A6	40	90	100	70	90	30	70	100
A7	75	75	80	80	80	70	80	75
A8	90	90	75	85	100	100	75	70
A9	95	100	95	100	65	70	75	95
A10	80	70	95	85	95	85	100	85

$$\max\left(q_{\text{im}}\right) \to x_i\left(q_{\text{im}}\right) = 1 \tag{4}$$

Furthermore, the determination of the minimum value for V_i and adoption of X_i=0 for the minimum value using Eq. (5). According to Eq. (6), the intermediate values lie between zero and one.

$$\min\left(q_{\text{im}}\right) \to x_i\left(q_{\text{im}}\right) = 0 \tag{5}$$

$$x_i\left(q_{ij}\right) = \frac{q_{ij} - \min\left(q_{\text{in}}\right)}{\max\left(q_{\text{in}}\right) - \min\left(q_{\text{in}}\right)} \tag{6}$$

where $X_j(q_{ij})$ denotes the membership degree of q_{ij} in V_i vector.

It is worth noting that a direct estimation of values within the zero to one range, indicative of degrees of association, might not accurately reflect the actual conditions. To address this issue, experts ascertain the lower bound (r_l) and the upper bound (r_u) using Eqs. (7) and (8), respectively.

$$\forall_{j=1,2,\ldots,m} \quad q_{\text{in}}\left(q_{\text{in}} \geq r_u\right) \to X_i\left(q_{\text{in}}\right) = 1 \tag{7}$$

$$\forall_{j=1,2,\ldots,m} \quad q_{\text{in}}\left(q_{\text{in}} \geq r_\text{l}\right) \to X_i\left(q_{\text{in}}\right) = 0 \tag{8}$$

Consequently, the remaining factors fall within the zero to one range. The findings of the FZMS are consolidated and presented in Table 6.

2.4.3 The SRMS for the Rockburst Phenomenon

The SRMS operates as a $n*n$ matrix, where the rows and columns are aligned with the significant factors contributing to success. Each member, S_{ij}, in the matrix represents the correlation between factors i and j, with values ranging from −1 to 1. The number of variables that constitute each key success factor is denoted by "n", which is identical to the total count of key success factors. S_i is a numerical vector that represents each essential success aspect. The following are three various ways in which these relationships between the i and j notions can present themselves: If the value of S_{ij} is positive, it signifies a positive correlation, implying that an increase in idea i results in an increase in concept j. Conversely, when S_{ij} is negative, it signifies a negative correlation, implying that an increase in idea i results in a drop in concept j. Finally, if S_{ij} is equal to zero, it indicates that there is no resemblance between the concepts (Rodriguez-Repiso et al. 2007). Consequently, to ascertain the values of S_{ij}, it is necessary to establish three crucial parameters. These parameters are as follows: the sign of S_{ij}, which reflects the nature of causality between the concepts; the magnitude of S_{ij}, which indicates the strength of mutual influence; and the directional aspect of S_{ij}, which indicates the reciprocal impact between different concepts.

The FZMS facilitates the conversion of numerical vectors generated by the IMS into fuzzy sets, hence aiding in the determination of the dual nature of relationships. Considering vectors V1 and V2, corresponding to factors 1 and 2, and the degrees of membership, X1(V)j and X2(V) j, these vectors exhibit a direct (progressive) relationship. According to Rodriguez-Repiso et al. (2007), the presence of an inverse relationship can be deduced when X1(V)j strongly resembles 1—X2(V)j for the majority or all of the variables associated to the two vectors, and vice versa, resulting in Sij being less than zero on the other hand. Hosseini et al. (2022b) utilize the concept of vector distance to ascertain the closeness of the relationship between two vectors.

The strength of the correlation between concepts 1 and 2 is supported by the closeness of the link between

Table 5 Expert opinions of the critical rockburst factors and their ranking

Category	Factor		Score	Rank	Rank in category
Operational factors	A1	Poor water management	1661	51	15
	A2	Uncontrolled blasting effects	1832	30	10
	A3	Inadequate post-grouting	1972	11	4
	A4	Blast-induced vibrations	1998	9	3
	A5	Inadequate perimeter blasting	1767	41	13
	A6	Inadequate geological mapping	2043	3	1
	A7	Inadequate energy control	2026	5	2
	A8	Inadequate monitoring of tunnel behaviour	1751	43	14
	A9	Lack of ventilation and gas control	1563	56	16
	A10	Blasting sequence and timing	1943	13	6
	A11	Vibration damage from nearby activities	1917	19	9
	A12	Lack of ground stress management	1938	15	7
	A13	Poor drilling and blasting practices	1797	34	12
	A14	Lack of pre-grouting	1805	32	11
	A15	Excessive explosive charges	1957	12	5
	A16	Lack of in situ stress measurements	1928	17	8
Geological factors	A17	Presence of geological structures (e.g. joints, fractures)	2104	1	1
	A18	Presence of rock seams and weak layers	1583	54	8
	A19	Geological anomalies	1686	49	7
	A20	High in situ stress	2013	8	3
	A21	Geological fault zones	1920	18	4
	A22	Rock quality variations	2032	4	2
	A23	High rockburst-prone rock types (e.g. high quartz content)	1700	47	6
	A24	Geological heterogeneity	1789	36	5
Safety and preparedness factors	A25	Lack of personal protective equipment (PPE)	2095	2	1
	A26	Neglecting safety culture	1605	53	12
	A27	Lack of rockburst risk assessments	1900	21	5
	A28	Inadequate pillar design and extraction plans	2025	7	2
	A29	Insufficient ground support inspections	1793	35	7
	A30	Lack of adequate training for personnel	1776	39	8
	A31	Inadequate risk mitigation measures	1895	22	6
	A32	Inadequate emergency response plans	1940	14	3
	A33	Neglecting microseismic monitoring	1576	55	13
	A34	Poor communication and warning systems	1716	46	11
	A35	Inadequate safety regulations and enforcement	1753	42	10
	A36	Lack of geophysical monitoring	1768	40	9
	A37	Poor hazard identification and reporting	1904	20	4
Engineering factors	A38	Inadequate rock mass characterisation	1808	31	7
	A39	Tunnel geometry and design	2026	5	1
	A40	Inadequate blast design	1786	37	8
	A41	Inadequate ground support systems	1885	23	2
	A42	Tunnel orientation and alignment	1698	48	11
	A43	Weak tunnel lining materials	1840	28	5
	A44	Unsupported or inadequately reinforced tunnel faces	1736	44	10
	A45	High excavation rates	1783	38	9
	A46	Improper drilling techniques	1839	29	6
	A47	Excessive tunnel spans	1847	27	4
	A48	Inadequate rock reinforcement	1861	25	3
	A49	Excessive overbreak	1682	50	12

Table 5 (continued)

Category	Factor		Score	Rank	Rank in category
Seismic and dynamic factors	A50	Amplification of ground motion	1802	33	5
	A51	Induced seismicity	1650	52	7
	A52	Stress redistribution during blasting	1729	45	6
	A53	Inadequate monitoring: Failing to implement real-time monitoring systems for stress, deformation, seismic activity or gas emissions	1992	10	1
	A54	Sudden energy release	1937	16	2
	A55	Rock mass response to dynamic loading	1871	24	3
	A56	Dynamic loading near geological structures	1857	26	4

Table 6 A summary of the FZMS calculation relevant to the critical rockburst factors

The FZMS								
Rockburst factor	Expert							
	1	2	3	4	5	6	7	8
A1	0.6	0.8	1	0	0.8	1	0.6	0
A2	0	0.166667	0.333333	0.333333	1	1	0.333333	0
A3	0.285714	1	0	0.285714	0.571429	0.142857	0.142857	0.428571
A4	0.571429	0	1	0.714286	1	1	1	0.285714
A5	0	0.833333	0	0	0.333333	1	0	0.666667
A6	0	0.666667	1	0	0.666667	0.333333	0	1
A7	0.5	0.5	1	1	1	0	1	0.5
A8	0.666667	0.666667	0.166667	0.5	1	1	0.166667	0
A9	0.857143	1	0.857143	1	0	0.142857	0.285714	0.857143
A10	0.333333	0	0.833333	0.5	0.833333	0.5	1	0.5

vectors V_1 and V_2, considering the similarity between the two vectors. This is represented by the SRMS through the factor S12. Various calculations are involved in assessing the intensity of relationships between directly related and inversely related vectors. For instance, when V_i and V_j exhibit a direct relationship, Eq. (9) is employed.

$$d_j = \left| X_1(V_j) - X_2(V_j) \right| \tag{9}$$

where, in this equation, the distance between the factors of two vectors of j is denoted by the symbol d_j. Through the use of Eq. (10), AD is determined to be the average distance between vectors V_1 and V_2.

$$\mathrm{AD} = \frac{\sum_{j=1}^{m} \left| d_j \right|}{m} \tag{10}$$

The similarity of S between the two vectors is based on Eq. (11):

$$S = 1 - \mathrm{AD} \tag{11}$$

where S = 1 signifies complete similarity and S = 0 implies maximum dissimilarity.

When there is an inverse link between V_1 and V_2, the procedure for determining the similarity is the same as it was before. Equation (12) is used to get the distance between the elements that are related to each other. According to Eq. (12), the distance between the factors has a connection that is inversely proportional to the vectors V_1 and V_2, respectively.

$$d_j = \left| X_1(V_j) - \left(1 - X_2(V_j)\right) \right| \tag{12}$$

Equation 10, employed for computing the mean distance between two vectors, and Eq. 11, utilised for assessing the similarity of S, remain consistently applicable. A value of S equal to one signifies perfect inverse similarity between the two vectors, whereas a value of S equal to zero shows the absence of inverse similarity between them. A summary of the findings of the SRMS, which includes an analysis of all 34 components, may be seen in Table 7.

Table 7 A summary of the SRMS calculation for ten rockburst factors

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
A1	–	0.509	0.648	0.371	0.797	0.765	0.892	0.668	0.447	0.643
A2	0.509	–	0.622	0.652	0.845	0.744	0.791	0.694	0.835	0.697
A3	0.648	0.622	–	0.757	0.736	0.724	0.831	0.797	0.792	0.757
A4	0.371	0.652	0.757	–	0.695	0.629	0.816	0.765	0.675	0.837
A5	0.797	0.845	0.736	0.695	–	0.774	0.787	0.657	0.784	0.710
A6	0.765	0.744	0.724	0.629	0.774	–	0.843	0.686	0.667	0.713
A7	0.892	0.791	0.831	0.816	0.787	0.843	–	0.660	0.843	0.672
A8	0.668	0.694	0.797	0.765	0.657	0.686	0.660	–	0.484	0.711
A9	0.447	0.835	0.792	0.675	0.784	0.667	0.843	0.484	–	0.717
A10	0.643	0.697	0.757	0.837	0.710	0.713	0.672	0.711	0.717	–

2.4.4 The Final Matrix of Success for the Rockburst Phenomenon

For the purpose of reviewing data and transitioning SRMS into FMS, expert insights are very necessary. More specifically, the focus should be placed on fuzzy numerical variables that indicate causal linkages amongst the major success elements (Rodriguez-Repiso et al. 2007). Not all of the important components that are portrayed in the matrix are connected to one another, and there is no discernible cause-and-effect relationship between them. Because of this, these insights serve the function of identifying all of the variables in the SRMS that display a cause-and-effect linkage. A synthesis of the data from the SRMS (Table 7) is used to construct the results of the FMS, which are shown in Table 8. The results, which provide a summary of the interconnections amongst the problematic parts based on expert assessments, are displayed in Table 8.

An examination of Table 8 highlights the causal relationship between factor 4 (blast-induced vibrations) and factor 10 (blasting sequence and timing). However, no such relationship exists between factors 7 and 9 (inadequate energy control and lack of ventilation and gas control). Null cells within the table signify the absence of a relationship between the respective factors. It is pertinent to note that the values presented in Table 8 remain consistent with those in Table 7. Negative signs within Table 8 indicate the presence of negative aspects associated with the factors. For better representation, a structure of FCM for ten rockburst factors is illustrated in Fig. 7.

2.4.5 Organizing the Graphical FCM of the Rockburst Phenomenon

Utilising the set values in row *i* and column *j* of the FMS, a purposeful FCM is visually depicted, illustrating the key success factors and their interrelationships, each denoted by a signed weight (Hosseini et al. 2022b).

In the context of the current study, the FMS construction is informed by the formation of the strength matrix and the integration of expert insights. The construction of the FCM may involve the incorporation of time series data and pertinent expert opinions. Figure 8 serves as an illustration of the cognitive map formulated based on the expert perspectives. It is important to note that the precise assessment of weights by professionals is essential to capture the complex relationships that exist between the components that are troublesome. The 34 components that were investigated are represented by the nodes in Fig. 8, and the rows illustrate the cause-and-effect interactions

Table 8 A summary of the FMS calculation for ten rockburst factors

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
A1	–			−0.771						
A2	0.509	–	0.622	0.652			0.791	0.694	0.835	0.697
A3			–	0.757				0.797		
A4	0.771	0.652		–	0.695	0.629	0.816	0.765	0.675	0.837
A5	0.797		0.736	−0.695	–	0.774		−0.657	−0.784	−0.710
A6		0.744	0.724	0.629	0.774	–			−0.667	−0.713
A7	0.892		−0.831	0.816	0.787		–			
A8			0.797	0.765		0.686	0.660	–	0.484	0.711
A9		0.835			0.784			0.484	–	0.717
A10		0.697	0.757		0.710	0.713				–

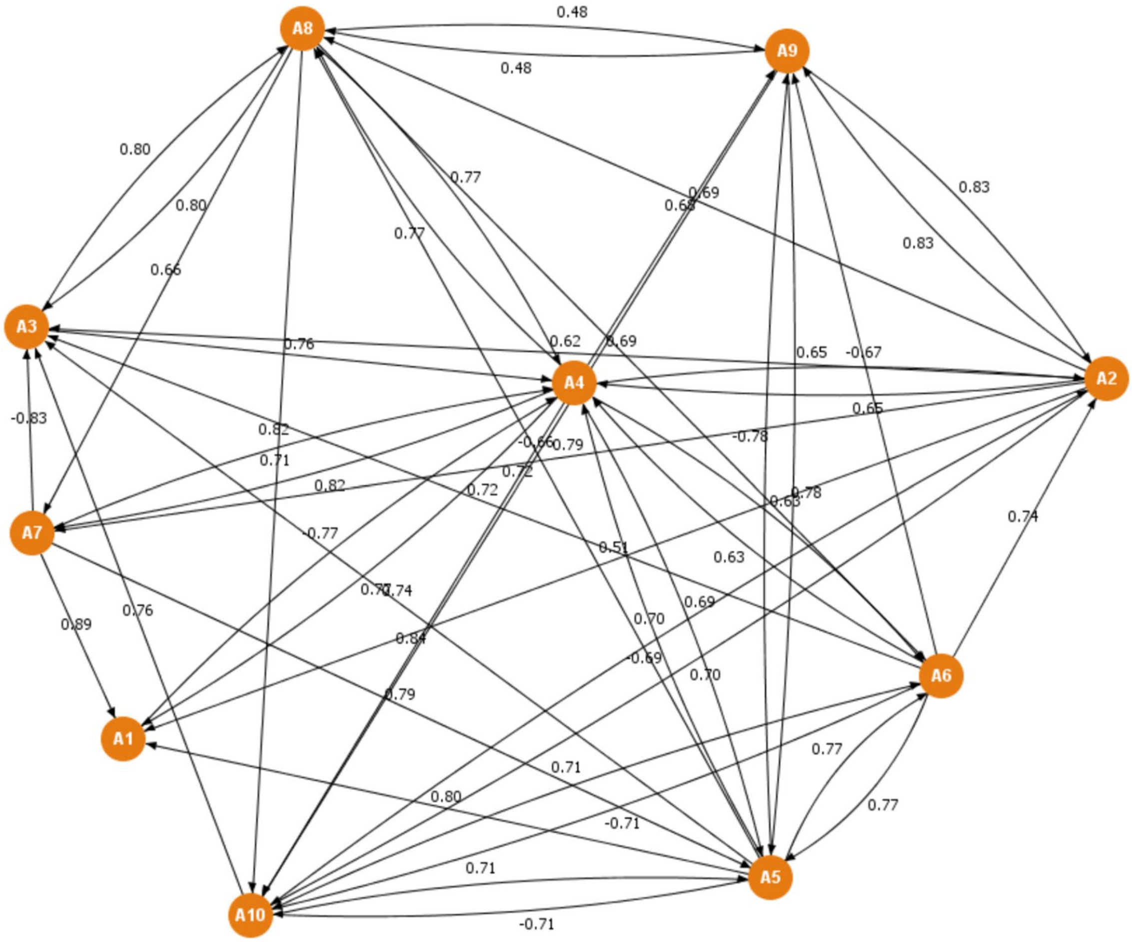


Fig. 7 The structure of FCM for ten rockburst factors

that exist between these problematic aspects. In addition, the numerical labels that are contained within each node correlate to the numbering of the factors that are presented in Table 1.

When the effectiveness of each component is taken into consideration (Table 8; Fig. 7), as well as the final ranking of factors, which is shown in Table 9, 11 out of the 56 factors provide the concept of negligible relations. A comprehensive overview of the ranking results is presented in Table 9.

3 Results and Discussion

In summary, numerous challenging elements have surfaced concerning rockburst occurrences in underground excavation ventures. This research has identified and examined an additional 56 critical rockburst factors related to underground excavation and construction. The Fuzzy Cognitive Map (FCM) analysis in this investigation, as illustrated in Table 9, highlights 'lack of rockburst risk assessments' as the foremost predicament within these projects. "Lack of rockburst risk assessments" is a critical factor contributing to the challenges faced in underground excavation projects. The absence of a comprehensive evaluation of rockburst risks can be attributed to various factors. One primary reason is the inadequacy of thorough geological mapping and characterisation, resulting in an incomplete understanding of the potential hazards. Insufficient attention to the dynamic loading and stress redistribution during blasting activities further compounds this issue, leading to an underestimation of potential rockburst risks.

To address this pressing concern, several key solutions can be implemented. First, there should be a focus on conducting detailed geological surveys and mapping, including a thorough analysis of structural properties and stress distributions. In addition, implementing real-time monitoring systems for stress, deformation and seismic activities would enable a proactive approach to risk assessment. Employing advanced technologies such as microseismic monitoring can enhance the detection and prediction of potential rockburst occurrences. Furthermore, fostering a robust safety culture

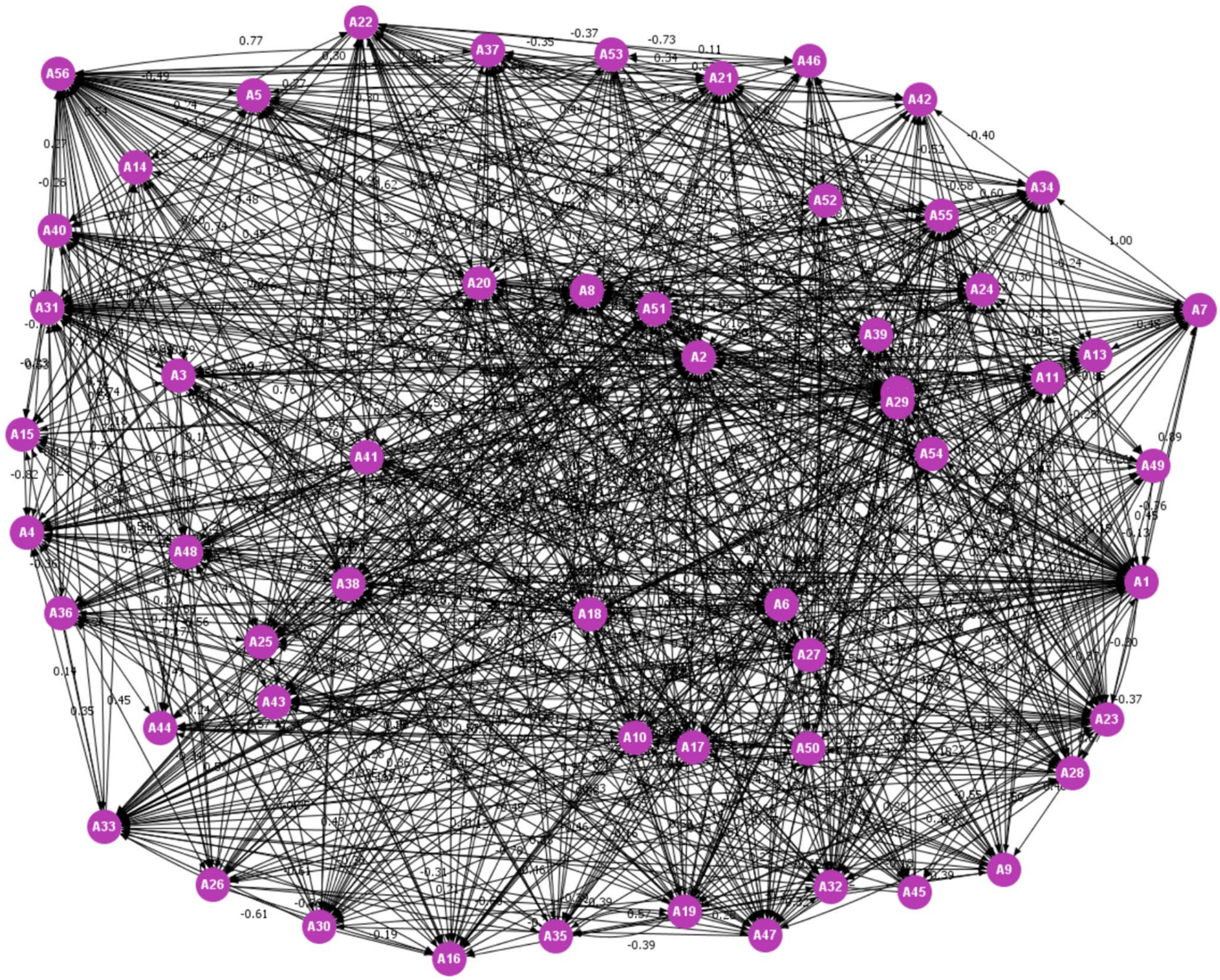


Fig. 8 The finalized FCM topology of the causal-and-effect of the critical rockburst factors

within the project team and establishing stringent safety regulations and enforcement mechanisms are crucial steps in mitigating the impact of this problem. By prioritizing comprehensive risk assessments, fostering a culture of safety, and leveraging cutting-edge monitoring technologies, the mitigation of the “Lack of rockburst risk assessments” can be effectively addressed, promoting safer and more efficient underground excavation/construction.

According to the constructed FCM, “high in-situ stress” ranks as the second most challenging factor. High in situ stress is a critical factor contributing to rockburst occurrences in underground excavations. The elevated stress levels in the surrounding rock mass create substantial pressure, leading to the sudden release of energy, thereby causing rock fracturing and potentially hazardous rockburst events. The excessive stress can exceed the strength of the rock mass, triggering sudden failures and instabilities, endangering the safety of workers and the integrity of the tunnel structure. To address the challenges posed by high in situ stress, several measures can be implemented. First, conducting thorough geological surveys and assessments to identify stress-prone zones can provide valuable insights into the potential risk areas. Implementing advanced monitoring techniques, such as stress measurements and microseismic monitoring, can help in the early detection of stress build-up, enabling timely interventions and preventive measures. Moreover, utilising effective ground support systems and reinforcement methods, such as rock bolting, shotcrete and rock anchors, can enhance the stability of the underground constructions, mitigating the adverse effects of high stress. In addition, implementing proper stress management strategies during excavation processes, including controlled blasting techniques and optimised drilling practices, can help alleviate the impact of high in situ stress. These proactive measures can collectively contribute to the reduction of rockburst occurrences and ensure the safety and stability of underground excavation

Table 9 Ranking of the rockburst factors resulted from FCM structure

Factor	Rank
Lack of rockburst risk assessments	1
High in situ stress	2
Presence of rock seams and weak layers	3
Rock quality variations	4
Geological heterogeneity	5
Geological anomalies	6
Geological fault zones	7
High rockburst-prone rock types (e.g. high quartz content)	8
Tunnel geometry and design	9
Tunnel orientation and alignment	10
Inadequate ground support systems	11
Unsupported or inadequately reinforced tunnel faces	12
Weak tunnel lining materials	13
Inadequate blast design	14
Improper drilling techniques	15
Excessive overbreak	16
Inadequate rock mass characterization	17
Inadequate rock reinforcement	18
Excessive tunnel spans	19
High excavation rates	20
Blasting sequence and timing	21
Blast-induced vibrations	22
Poor drilling and blasting practices	23
Inadequate energy control	24
Excessive explosive charges	25
Inadequate perimeter blasting	26
Uncontrolled blasting effects	27
Lack of in situ stress measurements	28
Inadequate monitoring of tunnel behavior	29
Lack of pre-grouting	30
Inadequate post-grouting	31
Vibration damage from nearby activities	32
Lack of ground stress management	33
Lack of ventilation and gas control	34
Inadequate geological mapping	35
Poor water management	36
Induced seismicity	37
Rock mass response to dynamic loading	38
Stress redistribution during blasting	39
Sudden energy release	40
Dynamic loading near geological structures	41
Amplification of ground motion	42
Inadequate monitoring: failing to implement real-time monitoring systems for stress, deformation, seismic activity, or gas emissions	43
Presence of geological structures (e.g. joints, fractures)	44
Inadequate emergency response plans	45
Lack of adequate training for personnel	46
Poor communication and warning systems	47
Neglecting safety culture	48
Inadequate risk mitigation measures	49
Lack of geophysical monitoring	50
Insufficient ground support inspections	51
Inadequate safety regulations and enforcement	52
Lack of personal protective equipment (PPE)	53
Poor hazard identification and reporting	54
Neglecting microseismic monitoring	55
Inadequate pillar design and extraction plans	56

projects. Table 10 summarizes the 15 rockburst factor, mitigation risks and their suggested strategies for addressing the challenges or minimizing associated risks.

4 Limitations and Future Directions

The examination concerning FCM usage in assessing pivotal factors contributing to rockbursts in subterranean construction offers valuable insights whilst also showcasing specific drawbacks and prospects for further investigation. Although the expertise of experienced industry practitioners enriches the development of the cognitive map, it introduces a potential bias, potentially overlooking alternative viewpoints or elements. Furthermore, the study's conclusions might lack applicability beyond the precise context under scrutiny, given the variability of rockburst influences across geological and operational settings. The intricacy of FCMs could impede their pragmatic utility for decision-making, particularly for individuals lacking specialised expertise. In addition, the reliance on qualitative data and professional judgments might curtail the model's resilience. Subsequent research endeavours could validate and fine-tune the FCM framework utilising empirical evidence, merging quantitative data to bolster the model's impartiality. Techniques involving dynamic modelling could capture the temporal progression of risk factors, whilst engaging stakeholders could enrich inclusivity and pertinence. Moreover, advancements in technology present avenues for real-time surveillance and decision-making systems, amplifying the insights provided by FCMs with actionable intelligence and predictive capabilities. Future research on rockburst accordance holds significant promise for advancing our understanding and management of this geotechnical challenge. Fundamental research studies with the help of more experts from different case studies are needed to discover new facts regarding this phenomenon. Exploring hybrid predictive models that incorporate cutting-edge

Table 10 The risk and solution relevant to 15 of the most important rockburst factors

Factor	Risk	Solution
Lack of rockburst risk assessments	Maximum	Employing advanced technologies, conducting comprehensive geological surveys and rock mass characterisation studies to identify potential rockburst hazards and assess the risk level associated with different areas of the tunnel, utilising advanced geomechanical modelling and simulation tools to predict rockburst occurrences and assess their potential impact on tunnel stability and safety, implementing standardised risk assessment methodologies, such as the Rockburst Risk Assessment Method (RRAM), to systematically evaluate the likelihood and consequences of rockbursts in the tunnelling environment
High in situ stress	Unprecedented	Conducting thorough geological surveys and assessments to identify stress-prone zones, implementing advanced monitoring techniques, implementing proper stress management strategies during excavation processes
Presence of rock seams and weak layers	Exceptional	Conducting comprehensive geological mapping and rock mass characterisation; implementing advanced geophysical exploration techniques; employing specialised ground support systems; ensuring effective monitoring of the excavation site through real-time monitoring systems
Rock quality variations	Extremely high	Comprehensive rock mass characterisation and geotechnical assessments; utilising advanced geotechnical testing methods, such as uniaxial and triaxial compression tests, Brazilian test and p-wave velocity test; implementing appropriate ground support systems tailored to the specific rock quality variations; employing reinforcement techniques such as rock bolting, shotcrete application and mesh installation; adopting pre-grouting and post-grouting practices
Geological heterogeneity	Very high	Employing advanced geological surveying techniques, such as 3D geological modelling and sophisticated geophysical investigations, the implementation of customised ground support systems, integrating a combination of effective rock bolting, strategic shotcrete application, and the installation of specialised mesh designed, the adoption of precise grouting techniques, including pre-grouting and post-grouting; establishing a robust and comprehensive monitoring system, continuous monitoring of stress variations, deformation patterns, and seismic activities
Geological anomalies	High	Conduct thorough geological surveys using modern technologies such as ground-penetrating radar, seismic imaging, and borehole logging; implement rock mass classification systems (e.g. RMR, Q-system); design and install appropriate ground support systems such as rock bolts, shotcrete, steel sets, and mesh based on the geological conditions encountered
Geological fault zones	Moderately high	Implementing advanced geological mapping techniques to identify fault zones accurately before excavation begins, using ground support systems such as rock bolts, shotcrete and mesh to reinforce areas prone to rock bursts; employing remote monitoring systems to continuously assess stress levels and detect potential rock burst hazards; utilising numerical modelling and simulation to predict and mitigate the impact of fault zones on excavation stability
High rockburst-prone rock types (e.g. high quartz content)	Above average	Utilising pre-conditioning techniques such as controlled blasting or stress relief drilling to reduce the inherent stress in high quartz content rock formations; implementing specialised ground support systems designed to withstand the unique challenges posed by high quartz content rocks, such as deformable rock bolts or flexible mesh

Table 10 (continued)

Factor	Risk	Solution
Tunnel geometry and design	Moderate	Optimising tunnel alignment and profile to minimise intersections with geological fault zones and high rockburst-prone rock types, implementing a larger tunnel cross-section to provide sufficient clearance and reduce stress concentration in high rockburst-prone areas
Tunnel orientation and alignment	Average	Conducting thorough geological surveys and studies to identify the most stable orientation and alignment for the tunnel in relation to geological features, such as fault zones and rock types prone to rock bursts, choosing tunnel orientations that minimise intersections with fault zones and avoid areas of known geological instability, aligning the tunnel along natural geological features, such as bedding planes or foliation, to reduce stress concentrations and minimise the likelihood of rock bursts
Inadequate ground support systems	Below average	Conducting comprehensive geotechnical assessments to determine the appropriate type and spacing of ground support systems required for the specific geological conditions of the tunnel; implementing redundant ground support systems, such as combination rock bolts with mesh or shotcrete, to provide multiple layers of reinforcement and enhance overall stability; regularly inspect and maintain ground support systems to ensure they remain effective throughout the lifespan of the tunnel
Unsupported or inadequately reinforced tunnel faces	Moderately low	Implementing immediate temporary support measures such as rock bolts, shotcrete, or mesh to stabilise unsupported tunnel faces until a permanent solution can be installed; prioritising the installation of ground support systems in critical areas of the tunnel face where instability is most likely to occur, such as near fault zones or in highly fractured rock masses
Weak tunnel lining materials	Low	Selecting high-strength tunnel lining materials such as reinforced concrete or steel ribs designed to withstand the anticipated loads and stresses experienced during tunnel operation; conducting rigorous material testing and quality control measures to ensure the strength and durability of tunnel lining materials meet or exceed design specifications
Inadequate blast design	Very low	Conducting comprehensive geological surveys and rock mass classification assessments to better understand the rock conditions and optimise blast designs accordingly; utilising advanced blasting techniques such as perimeter blasting, smooth blasting, or presplitting to control ground vibrations, reduce overbreak, and minimise the risk of rockburst; implementing blast design parameters such as hole diameter, spacing, and stemming length tailored to the specific rock characteristics and tunnel geometry to ensure effective fragmentation and minimal ground disturbance; employing specialised explosive products designed for use in challenging geological conditions, such as high quartz content rocks, to achieve desired fragmentation whilst minimising energy release and ground disturbances
Improper drilling techniques	Negligible	Providing thorough training and certification programs for drilling personnel to ensure they are proficient in proper drilling techniques, equipment operation, and safety protocols; implementing regular equipment maintenance and inspection schedules to ensure drilling machinery is in optimal working condition and capable of achieving accurate hole alignment and depth; utilising advanced drilling technologies such as laser-guided drilling systems or automated drilling rigs to improve drilling accuracy and consistency

technologies, such as machine learning and artificial intelligence, together with FCM, could provide a more nuanced and accurate forecast of potential rockburst occurrences. There is potential to extend the FCM methodology to address emerging challenges in underground excavation, such as the impact of new technologies and evolving environmental considerations. Continuous validation and calibration of the FCM with empirical data from various excavation projects would strengthen its reliability, positioning it as a robust tool for proactive rockburst prevention and management. Furthermore, integrating real-time monitoring systems and sensor technologies into excavation sites could enhance early warning systems, allowing for timely preventive measures and, therefore, minimising the risks associated with rockburst. This holistic approach, incorporating advanced technologies and continuous refinement of models, presents a pathway toward more effective and proactive management of rockburst occurrences in underground excavation projects.

Furthermore, we duly acknowledge the recommendation for advanced geotechnical testing, encompassing both uniaxial and triaxial compression tests. We understand the significance of integrating true triaxial compression testing into our testing protocol to capture the intricate three-dimensional stress states prevalent in underground environments. Studies such as those conducted by Gong et al. (2018) have emphasised the notable impact of intermediate principal stress on crack propagation around tunnel peripheries, thus highlighting the imperative nature of considering three-dimensional stresses. The incorporation of true triaxial compression testing into our experimental setup will serve as a valuable addition to further elucidate the mechanisms governing rockburst occurrences. It is noteworthy that the increase in temperature with depth in mines, along with thermal gradients, constitutes a relevant factor influencing rockburst incidents. Recent research by Moravej et al. (2023) underscores the importance of thermal conditions in triggering spalling and rockburst events under comparable confining stress. We recognise the significance of integrating temperature effects into our framework, either by embedding thermal considerations into the proposed Finite Continuum Method (FCM) or by addressing it as a critical factor influencing rockburst susceptibility. Subsequent studies will delve into methodologies to integrate thermal effects into our predictive models, thereby augmenting their accuracy and applicability in deep mining environments.

By addressing these limitations and focusing future research efforts on these key areas, we endeavour to advance the current understanding of rockburst mechanisms and develop more robust predictive frameworks for mitigating rockburst hazards in underground mining operations.

5 Conclusion

In conclusion, this paper delved into the complexities of rockburst occurrences in underground excavation/construction through a comprehensive approach. The initial identification of 89 locally derived critical factors, distilled through interviews with engineers and executive agents, culminated in the utilisation of Fuzzy Cognitive Maps (FCM) methodology. A meticulous selection process narrowed down the investigation to 56 of the most significant elements, characterised by high frequency and severe implications. The resulting cognitive map, enriched with fuzzy weights assessed by specialists, provided valuable insights into the intricate connectivity amongst components contributing to the rockburst issue. Notably, certain factors were found to lack a clear cause-and-effect relationship with other components, highlighting the nuanced nature of the problem. Ultimately, the study pinpointed the top five critical factors influencing rockburst occurrences in underground excavations: the lack of rockburst risk assessments, high in situ stress, presence of rock seams and weak layers, rock quality variations, and geological heterogeneity. These findings contribute significantly to the advancement knowledge in geotechnical and mining engineering, offering insights that can foster safer practices and serve as a guiding resource for decision-makers in the field.

Acknowledgements The authors wish to extend their appreciation to the University of Technology Sydney (UTS) for the support and for making this research possible.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Data availability Data available on request from the corresponding author.

Declarations

Conflict of Interest The authors declare there is no conflict of interest for this research.

References

Afraei S, Shahriar K, Madani SH (2019) Developing intelligent classification models for rock burst prediction after recognizing significant predictor variables: Literature review and data preprocessing procedure. Tunn Undergr Sp Technol 83:324–353

Axelrod R (2015) Structure of decision: the cognitive maps of political elites. Princeton University Press, Princeton

Bakhtavar E, Hosseini S, Hewage K, Sadiq R (2021) Green blasting policy: simultaneous forecast of vertical and horizontal distribution of dust emissions using artificial causality-weighted neural network. J Clean Prod 283:124562

Barton N, Lien R, Lunde J (1974) Engineering classification of rock masses for the design of tunnel support. Rock Mech Felsmechanik Mécanique Des Roches. https://doi.org/10.1007/BF01239496

Blake W (1972) Rock burst mechanics, quarterly color. Sch Mines 67, Vol. 67:1, 35-37.

Blake W, Hedley DGF (2003) Rockbursts: case studies from North American hard-rock mines. SME, 121: 18-23.

Cai M (2013) Principles of rock support in burst-prone ground. Tunn Undergr Sp Technol 36:46–56

Cook NGW (1965) A note on rockbursts considered as a problem of stability. J South Afr Inst Min Metall 65:437–446

Ming DL, Ping LC, Long MZ, Shi GM (2009) Prevention and forecasting of rock burst hazards in coal mines. Min Sci Technol. https://doi.org/10.1016/S1674-5264(09)60109-5

Evariste M (2019) A review on rockburst as a serious safety problem in deep underground mines and other excavation projects. Int J Eng Res. https://doi.org/10.17577/ijertv8is110194

Fanjie Y, Hui Z, Haibin X et al (2022) Numerical simulation method for the process of rockburst. Eng Geol 306:106760

Farhadian H (2021) A new empirical chart for rockburst analysis in tunnelling: tunnel rockburst classification (TRC). Int J Min Sci Technol 31:603–610

Feng G, Xia G, Chen B et al (2019a) A method for rockburst prediction in the deep tunnels of hydropower stations based on the monitored microseismicity and an optimized probabilistic neural network model. Sustain. https://doi.org/10.3390/su11113212

Feng X-T, Xiao Y-X, Feng G-L et al (2019b) Study on the development process of rockbursts. Chinese J Rock Mech Eng 38:649–673

Gao W (2010) Prediction of rock burst based on ant colony clustering algorithm. Chin J Geotech Eng 32:874–880

Gill DE, Aubertin M, Simon R (1993) A practical engineering approach to the evaluation of rockburst potential. Rockburst Seism Mines Balkema, Rotterdam, pp 63–68

Gong F, Luo Y, Li X et al (2018) Experimental simulation investigation on rockburst induced by spalling failure in deep circular tunnels. Tunn Undergr Sp Technol 81:413–427

Guo R, Yu R (2002) Design of support work in drift having rockburst danger. China Min Mag 11:23–26

He F (2005) Study on geological hazards in tunneling of deep-buried long tunnels at qinling-dabashan orogen of the three gorges reservoir water diversion project. Ph.D Thesis. China Academy of Geological Sciences, Beijing, China (in Chinese).

Hosseini S, Lawal AI, Kwon S (2023) A causality-weighted approach for prioritizing mining 4.0 strategies integrating reliability-based fuzzy cognitive map and hybrid decision-making methods: a case study of Nigerian Mining Sector. Resour Policy. https://doi.org/10.1016/j.resourpol.2023.103426

Hosseini S, Poormirzaee R, Hajihassani M (2022a) Application of reliability-based back-propagation causality-weighted neural networks to estimate air-overpressure due to mine blasting. Eng Appl Artif Intell 115:105281. https://doi.org/10.1016/j.engappai.2022.105281

Hosseini S, Poormirzaee R, Hajihassani M, Kalatehjari R (2022b) An ANN-fuzzy cognitive map-based Z-number theory to predict flyrock induced by blasting in open-pit mines. Rock Mech Rock Eng 55:1–18

Hosseini SS, Poormirzaee R, Moosazadeh S (2022c) Study of hazards in underground mining: using fuzzy cognitive map and Z-number theory for prioritizing of effective factors on occupational hazards in underground mines. Iran J Min Eng 56:11–20

Hou FL, Liu XM, Wang MQ (1992) Discussion on rockburst origin and degree. In: Proceedings of the 3rd Academic Conference on National Rock Dynamics. Technical University of Surveying and Mapping Press, Wuhan. pp 448–457

Kaiser PK, Tannant DD, McCreath DR (1996) Canadian rockburst support hand-book, Geomechanics Research Centre. Ontario Laurentian Univ, Sudbury

Kaiser PK, Tannant DD, McCreath DR, Jesenak P (1992) Rockburst damage assessment procedure. In: International symposium on rock support, pp 639–647

Kosko B (1986) Fuzzy cognitive maps. Int J Man Mach Stud 24:65–75

Li XB (2014) Rock dynamics fundamentals and applications. Sci Beijing, Science Press China, 649.

Li XB, Yao JR, Gong FQ (2011) Dynamic problems in deep exploitation of hard rock metal mines. Chin J Nonferrous Met 21:2551–2563

Mahmoud M (2023) Physical modelling of spalling failure in underground structures, Ph.D. Thesis, The University of Queensland

Moravej S, Mutaz E, Serati M, Williams DJ (2023) Coupled Thermo-Mechanical Study of Crack Initiation Stress Threshold in Porous Sandstone. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, p 12022

Mutaz E, Serati M, Williams DJ (2024) Crack mode-changing stress level in porous rocks under polyaxial stress conditions. Acta Geotech. https://doi.org/10.1007/s11440-023-01994-2

Obert L, Duvall WI (1967) Rock mechanics and the design of structures in rock (no title)

Ortlepp WD (2005) RaSiM comes of age—a review of the contribution to the understanding and control of mine rockbursts. In: Proceedings of the sixth international symposium on rockburst and seismicity in mines, Perth, Western Australia, pp 9–11

Ortlepp WD (1997) Rock fracture and rockbursts: an illustrative study. South African Institute of Mining and Metallurgy, Johannesburg

Ortlepp WD, Stacey TR (1994) Rockburst mechanisms in tunnels and shafts. Tunn Undergr Sp Technol 9:59–65

Palmström A (1995) Characterizing rock burst and squeezing by the rock mass index. In: International conference in design and construction of underground structures

Papageorgiou EI, Kannappan A (2012) Fuzzy cognitive map ensemble learning paradigm to solve classification problems: application to autism identification. Appl Soft Comput 12:3798–3809

Peng Z, Wang YH, Li TJ (1996) Griffith theory and rock burst of criterion. Chin J Rock Mech Eng 15:491–495

Potvin Y, Hudyma M, Jewell RJ (2000) Rockburst and seismic activity in underground Australian mines-an introduction to a new research project. In: ISRM international symposium. ISRM, p ISRM-IS

Pu Y, Apel DB, Liu V, Mitri H (2019) Machine learning methods for rockburst prediction-state-of-the-art review. Int J Min Sci Technol 29:565–570

Qiu Y, Zhou J (2023) Short-term rockburst prediction in underground project: insights from an explainable and interpretable ensemble learning model. Acta Geotech. https://doi.org/10.1007/s11440-023-01988-0

RibeiroeSousa L, Miranda T, LealeSousa R, Tinoco J (2017) The use of data mining techniques in rockburst risk assessment. Engineering. https://doi.org/10.1016/J.ENG.2017.04.002

Rodriguez-Repiso L, Setchi R, Salmeron JL (2007) Modelling IT projects success with fuzzy cognitive maps. Expert Syst Appl. https://doi.org/10.1016/j.eswa.2006.01.032

Russenes BF (1974) Analysis of rock spalling for tunnels in steep valley sides, Master's Thesis, Norwegian Institute of Technology, Department of Geology, Norway, 247,

Singh B, Goel RK (1999) Rock mass classification: a practical approach in civil engineering. Elsevier, Amsterdam

Solak T (2009) Ground behavior evaluation for tunnels in blocky rock masses. Tunn Undergr Sp Technol 24:323–330

Tan YA (1988) Mechanism research and comprehensive evaluation of rockburst. Dissertation, Xi'an College of Geology, Xi'an, China (in Chinese).

Thrush PW (1968) A dictionary of mining, mineral, and related terms. US Bureau of Mines, Washington

Wang J, Zhang J (2010) Preliminary engineering application of microseismic monitoring technique to rockburst prediction in tunneling of Jinping II project. J Rock Mech Geotech Eng 2:193–208

Wang LS, Li TB, Xu J et al (1999) Rockburst and its intensity classification of Erlangshan highway tunnel. Highway 28:41–45

Wang X, Dong L, Fu Y (2009) Prediction of possibility and the level of rockburst based on uncertain average gradted analysis method. Keji Daobao/sci Technol Rev 27:78–81

Xiating F, Binrui C, Chuanqing Z, et al (2013) Mechanism, warning and dynamic control of rockburst development process; Science Press: Beijing, China.

Xue R, Liang Z, Xu N, Dong L (2020) Rockburst prediction and stability analysis of the access tunnel in the main powerhouse of a hydropower station based on microseismic monitoring. Int J Rock Mech Min Sci. https://doi.org/10.1016/j.ijrmms.2019.104174

Zhao X, Zhang S, Zhu Q et al (2020) Dynamic and static analysis of a kind of novel J energy-releasing bolts. Geomat Nat Hazards Risk 11:2486–2508

Zhen-Yu T (1988) Support design of tunnels subjected to rockbursting. In: ISRM International Symposium. ISRM, p ISRM-IS

Zhou J, Li X, Mitri HS (2018) Evaluation method of rockburst: state-of-the-art literature review. Tunn Undergr Sp Technol 81:632–659

Zhou J, Li XB, Mitri HS (2017) A critical survey of empirical methods for evaluating rockburst potential. In: Proc 15th IACMAG, Wuhan, China, 18–22

Zhou J, Zhang Y, Li C, et al (2024) Rockburst prediction and prevention in underground space excavation. Undergr Space 14:70–98. https:// doi. org/ 10. 1016/j. undsp. 2023. 05. 009.