Implications to secure mineral supply for clean energy technologies for developing countries: A fuzzy based risk analysis for mining projects

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Implications to Secure Mineral Supply for Clean Energy Technologies for Developing Countries: A Fuzzy Based Risk Analysis for Mining Projects

Abstract

Cleaner energy production relies on the sustainable supply of minerals, and some of them have critical importance due to limited reserves and geopolitics. Ensuring a constant supply of these minerals, especially critical minerals, is becoming an increasingly important issue. With limited resources, capacities, and foreseeable increasing demands, this becomes an uphill task, particularly for developing countries. Concurrent to fulfilling the ever-growing demands to supply minerals in an economically viable, socially beneficial, and environmentally responsible manner, delays or stoppages due to various risks affiliated with the mining industry can affect the supply chain of minerals and other dependent components in the overall process to generate cleaner energy to achieve sustainability targets. The risks arising throughout the life cycle of mining projects are not always adequately addressed, which hinders the cleaner production of the minerals and, in turn, hamper the sustainable development of the mining industry. Therefore, identification, prioritization, and future remediation plans for probable risks related to the mineral supply chain, as well as risks associated with mining projects, are important. This work classifies 39 different risks characterized in seven major groups: economic and financial risks, environmental and climate, health and safety, management, political and legal, social, and technical and operational. A fuzzy logic-based methodology is applied to prioritize the risks associated with the mining projects. Each risk is evaluated independently to be prioritized in chronological order based on its relevance, which is determined by its likelihood of occurrence and impact. Results reveal that the technical and operational risks and economic and financial risks take precedence over those related to political and legal, social, environmental and climate, health and safety, and managerial groups. The work presented in this paper can help policy implementation and the mining industry to develop plans to address these risks beforehand and minimize the impact on the supply chain of critical minerals for cleaner production.

Keywords: Minerals supply chain; cleaner energy transition; risk assessment; mining projects; cleaner mineral production

1. Introduction

The mining industry falls among resource-intensive industries, making a significant contribution to the world economy. According to the World Bank report “Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition (Hund et al., 2020)”, the production of various minerals and metals, such as lithium, cobalt, graphite, indium, vanadium, and nickel, is expected to increase up to 964%, 585%, 383%, 241%, 173%, 108% by 2050, respectively. These minerals and metals are becoming more valuable due to their integral role in cleaner energy transmission, and the growing demand for clean energy technologies justifies the projections. The report also estimates that over 3 billion tons of minerals and metals will be needed to deploy wind, solar, geothermal power, and energy storage to achieve the Paris Agreement’s goal of keeping global warming below 2°C. Minerals and metals needed for clean energy technologies will be sourced from resource-rich developing countries yet to tap their mineral reserves. Due to the rapid global transition to heavily mineral intensive low-carbon technologies, more mining will have to be done in a safe, green, and climate-smart manner as a solution to combat climate change (Jiskani et al., 2021a; Jiskani et al., 2022).

It is well recognized that the rising demand for mineral resources not only expands the scale of production (Jiskani et al., 2020a) but also the complexity of mining projects (Dubiński, 2013), resulting in a plethora of decision problems involving risks and uncertainties (Chinbat and Takakuwa, 2009). An intensive mining process results in higher risks during operations and more resources usage. It also leads to the risks of interaction between the mining system and other components of sustainable mining, including the economy, environment, community, safety, and efficiency (Jiskani et al., 2020a; Tubis et al., 2020). The influence of risks hindering project goals places tremendous strain on the overall success of the project. It is because the risks affiliated with mining failures may also disrupt the likelihood of achieving desired sustainable goals from the overall operation. In the first place, a sustainable mining operation ensures greener operation and plays a role in cleaner energy production. Therefore, to achieve cleaner energy production goals based on critical minerals mining activities, it is crucial to identify potential risks and conduct a risk assessment in order to avoid, mitigate, reduce or control them by developing risk management plans (Amoatey et al., 2017).

Scholars around the world have advocated the importance of risk assessment for various stages and components of mining projects. For instance, Lèbre et al. (2019) argued that growing consumer demand is causing worries about metal availability and criticality. Therefore, mining projects have to confirm their ability to assess, manage and minimize risks. Otherwise, the supply of energy transition metals will be hindered, making the shift to a low-carbon future even more difficult (Lèbre et al., 2020). Badri et al. (2012) reviewed studies on risk management of mining projects and concluded that many large-scale mining projects have failed due to neglecting or underestimating the associated risks. Therefore, the risk management tools should be appropriately utilized to enhance the reliability of decisions based on them for the success of mining projects. Verma and Chaudhari (2016) highlighted key findings from the literature on risk assessment techniques adopted in the mining industry. The authors point out that the methods applied are not holistic, generalized, and fully capable of overcoming the uncertainties in the data, which lead to an inefficient analysis process, creating obstacles to obtaining the output that can be used to develop management strategies and implement on the ground to improve the risk assessment process. Developing a robust risk assessment technique to improve the risk assessment process has become necessary to prepare mitigation plans for treatment and prevention of undesired consequences in an effective and timely manner. Researchers also stressed that traditional risk management systems often fail to adequately address the specific challenges of the mining industry, such as human capital, climate changes, and new technologies (Domingues et al., 2017).

There have been several studies undertaken using techniques for quantitative risk assessment regarding mining projects from various perspectives. Banda (2019) proposed a risk assessment framework for mining projects in Zambia that integrates the analytic hierarchy process, expert questionnaire, and sensitivity analysis. The method determined the impact of risks, probability scores and identified negligible and tolerable risks that are volatile. Lèbre et al. (2019) offered a method to assess the environmental, social, and governance risks critical to developing new mining projects. Based on a purposive sampling questionnaire, Amoatey et al. (2017) used a risk severity matrix to assess the likelihood of occurrence and degree of impact of the risk factors on mining projects in Ghana. For polish mining enterprises, Jonek-Kowalska and Nawrocki (2019) assessed operational risks from the viewpoint of long-term and sectoral research using a fuzzy evaluation model. It was found that the operational risk, in the long run, has been changing, primarily in the area of human resources potential from the scope of financial resources evaluation. Moreover, the holistic level of risk is influenced by the changes in the level of tangible investments and human resources. A fuzzy synthetic evaluation method was proposed to analyze risks impeding sustainable mining in Pakistan (Jiskani et al., 2020a), classifying risks into very high, high, and medium priority levels. The study concludes that if the top priority risks, especially operational, technical, organizational, managerial, economic, and financial, health and safety, and environmental risks, are not well managed, the challenges faced by Pakistan to achieve sustainable mining practices will continue to rise with time. Thus, risk management planning should be strengthened to ensure current and future mines obtain sustainably certification.

Other quantitative risk assessment studies conducted in the mining industry have focused on several aspects of risks, such as safety, water inrush, and operational. For example, Gul et al. (2019) proposed a Pythagorean fuzzy VIKOR based safety risk assessment approach to conduct a case study in Turkey's underground copper and zinc mine. Tripathy and Ala (2018) assessed safety risks in underground coal mines of India using a fuzzy reasoning approach based on triangular membership functions that categorized the risks in the ranking of their respective importance. A fuzzy comprehensive evaluation system was established by Sun and Xue (2019) for risk assessment of floor water inrush in deep mines in China. To overcome deficiencies of crisp risk score used in the classical decision matrix method, Iphar and Cukurluoz (2020) introduced a fuzzy safety evaluation method based on the Mamdani algorithm to enhance the risk assessment process in mechanized coal mines in Turkey. For post-mining land restoration risk management regarding the quantitative risk assessment, Spanidis et al. (2020) presented a hybrid multicriteria decision making methodology combining AHP and TOPSIS. In China, investment risks were assessed at a gold mine using an extended TOPSIS method with linguistic neutrosophic numbers (Liang et al., 2017). According to gathered source data and calculated input criteria, Nawrocki and Jonek-Kowalska (2016) used three fuzzy sets for input variables and five fuzzy sets for output variables with triangular membership function to assess operational risk in coal mining enterprises in Central and Eastern Europe.

The literature establishes that various qualitative, quantitative, and hybrid risk assessment methodologies have been successfully applied for different types of risk assessments. When applying traditional methods, experts encounter difficulties providing a precise rating, which may not yield satisfactory results due to the high uncertainty level (Jiskani et al., 2020b). As a result, fuzzy logic-based methodologies are widely used to overcome the shortcomings of classical methods (Gul and Ak, 2018). Fuzzy logic was introduced by Zadeh (1965) to interpret uncertainties emerging from real situations (Petrović et al., 2020). Applications of membership functions describe fuzzy logic and deal with uncertainty and inaccuracy in expert judgment (Yazdi and Zarei, 2018). The two most commonly used membership functions are triangular and trapezoid due to their simplicity and computational efficiency. These fuzzy membership functions are applied to interpret risk terms and develop risk assessment methodologies in order to make results more scientifically convincing (Chen et al., 2021). In several circumstances, using a trapezoidal membership function is considered more reasonable than a triangular membership function (Glensk and Madlener, 2018).

The academic debate over project risk assessment in the mining sector is rather weak, which needs the attention of researchers (Amoatey et al., 2017; Banda, 2019). On the one hand, there is a lack of extensive risk assessment modeling for the mining industry compared with other sectors. On the other hand, previous models are site and application-specific, limiting their applicability in mining projects from a broader point of view. The lack of risk assessment methodologies for mining projects calls for further research since very little research has been conducted to address the overall broader challenges and risks the mining industry faces. Prompt and efficient implementation of the risk assessment and management process is conducive to the success of the project (Domingues et al., 2017). More research is particularly important since mining projects are prone to a high risk of project failure due to their scale, complexity, and high cost (Chinbat and Takakuwa, 2009; McLellan and Corder, 2013). Mines are associated with a variety of risks, each with its own set of characteristics and a varying level of complexity. These risks could result in overruns, delays, unsatisfactory results, total failure, or even a negative impact on the project and company reputation. Any type of failure can result from poor or inadequate risk assessment by the management of engaging companies, regulatory bodies, and public representatives. If the associated risks of mining projects are not appropriately assessed at the commencement of operation and managed throughout the operation lifetime, they will hinder the supply of minerals for low-carbon technologies worldwide. As a result, it is required to implement a timely and effective risk management strategy in mining projects to reduce uncertainty and improve decision-making. In-depth risk analysis and devising mechanisms to conduct such analysis will result in longevity and smooth operation of the current and future mining projects. The analyses help stakeholders make rational decisions, identify high-risk areas to be addressed, and opt for remedial solutions without disrupting the supply chain of critical minerals. Thus, risk management is necessary to ensure that mining projects in developing countries are successful due to more uncertainty in regulation and public policy implementation related to mining. This makes the research on risk assessment in the mining sector particularly important, as emphasized by the researchers (Tubis et al., 2020).

To respond to this current need in this field, this research presents a novel approach based on fuzzy logic for prioritizing the most critical risks in order to implement risk management strategies, such as risk avoidance, risk transfer, risk acceptance, risk escalation, and risk mitigation. This refers to the efforts to eliminate risks or mitigate their impact on the project. The developed tool will make it easier to work on developing risk management skills and processes so that risk is fully integrated into business strategy and strategic directors take the lead in defining a clear risk threshold. Conclusively, the present study has a two-fold contribution. The first objective is to present a novel approach to assess the risks of mining projects in developing countries to maintain a sustainable supply of critical minerals. The second objective is to provide an overview of the problems in the mining sector that may impede the future development of mining projects to achieve sustainable operations. A three-step research approach was used to achieve the proposed objectives.

- **Preliminary phase:** A literature review was conducted to identify all reported risks that influence a mining project at any stage of operation. A total of 39 risks were selected and classified into 7 groups that cover all the major aspects of a mining project.
- **Intermediate phase:** A questionnaire was developed and distributed to mining professionals all over the world. Data collected over a nine-month period from 92 participants from developing countries was gathered and used for the analysis. The experts evaluated each risk by rating two parameters: *the likelihood of occurrence* and *the impact on mining project objectives*. Their responses were weighed according to their professional experience. The weighted average technique was applied to calculate a final score for each risk parameter:
- **Final phase:** Since analyzing the risk is not simple due to inaccurate and vague data, the methodology used in this study is based on fuzzy logic to cope with uncertainty and imprecision in analyzing the risk. The risk assessment model was developed and implemented in MATLAB Fuzzy Logic Toolbox. This model calculates the relevance of each risk based on the final scores obtained for each of the two risk parameters. The approach enables the prioritization of risks considered the most critical to ensure the success of the mining projects.

This work serves as a case study for the mining sector in developing countries, as they share common risk factors. It will help mining professionals to take appropriate measures to overcome the most influential risks on a priority basis to ensure a constant supply of minerals for clean energy production. The following section explains the methodology opted for conducting this work. The succeeding section presents the result analysis and discussion. The final section concludes the study.

2. Research approach

The main objective of this model is to assess the priority of action for the risks that can influence a mining project and disrupt the mineral supply chain. The assessed risks prioritization will help develop appropriate response strategies to achieve the success of the mining projects. The details of each phase are described in the following sections (Fig. 1).

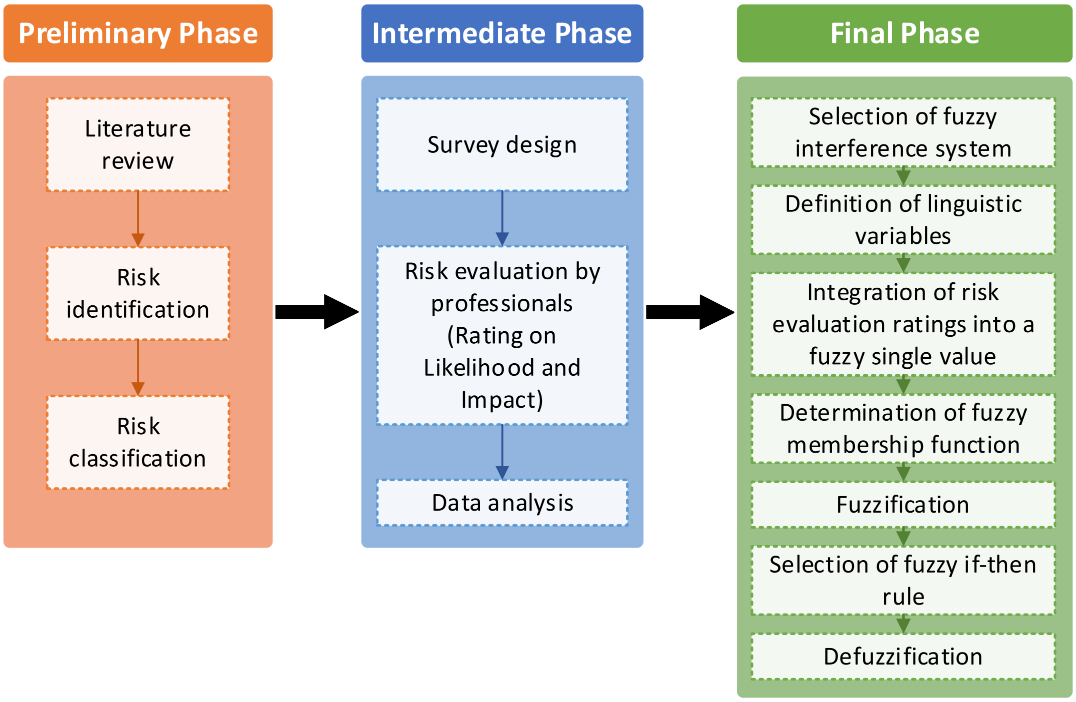

Fig. 1. Fuzzy assessment model.

2.1 Risk identification

The approach suggested in this work starts with identifying critical risks that can affect mining projects in developing countries. Modern mining projects operate in volatile external and internal environment challenges (Ivanova, 2019), resulting in numerous risks of production instability, loss of capital, technical challenges, cash flow of a mining business, interactions between government and mining enterprises, and others (Banda, 2019; Jiskani et al., 2020a). The risks were selected through a comprehensive literature review. They were incorporated into a questionnaire to be assessed by the professionals. Fig. 2 is a Risk Breakdown Structure (RBS) that coincides with the categorization followed by the literature to improve the risk identification process. Risks related to mining projects are divided into seven major groups.

Fig. 2. Risk breakdown structure.

2.2 Survey design and analysis of the respondents’ profiles

The anonymous questionnaire designed for this study aims to allow mining professionals to assess the risks that influence mining projects. The questionnaire, composed of two sections, was published in Google Forms to collect the data. In the first section, respondents were asked three questions about their country, job title level, and years of experience to determine their profile.

Mining professionals involved in the study are from various parts of the world (Fig. 3). From 30 developing countries, the most significant number of responses are from professionals working in Peru (10.87%), Chile (9.78%), India (8.70%), and Pakistan (7.61%).

Peru is a major mineral exporter in the world. It stands out as the world's sixth-largest producer of gold, the third-largest producer of silver, the second-largest producer of copper, the fourth-largest producer of lead, and the third-largest producer of zinc. Similarly, mining is also considered one of the most important industries contributing to Chile`s resource production and is well-known worldwide (Solminihac et al., 2018). Chile is the world's leading copper producer, and the Antofagasta Region in northern Chile is home to the country's richest mineral deposits. Mining has resulted in a substantial increase in income and employment opportunities in Chile (Tapia et al., 2018). The mining industry in India is also growing with vast quantities of natural resources, highlighting the massive coal reserves, becoming the third-largest reserve in the world (Makkhan et al., 2020). Pakistan is a country with numerous mineral deposits that are still to be exploited. The mining industry in this country has become an activity of significant economic potential. It has the potential to make a substantial contribution to the economy in the near future (Ali and Ur Rehman, 2020; Jiskani et al., 2021b).

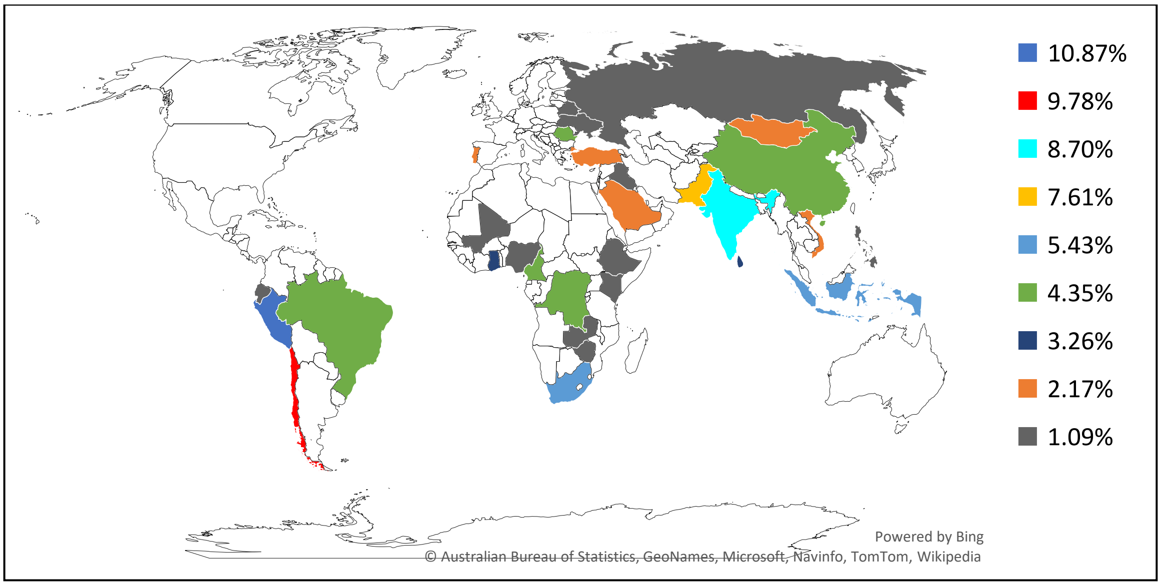

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Fig. 3. World map indicating countries of the respondents.

Fig. 4 shows the job title type and experience of mining professionals. The breakup of their positions in the industry shows that the most common respondents are engineers, educators (involved in teaching/research), managers, and consultants. They have worked in the industry for more than 21 years, less than 5 years, and between 11-16 years.

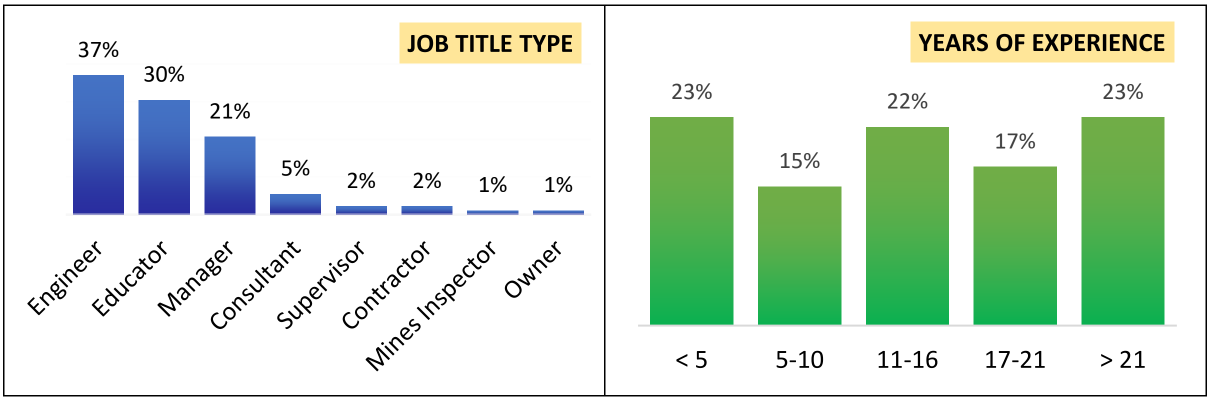


Fig. 4. Job title and experience of participants.

In the second section, the professionals assessed all the 39 risks according to two variables: the likelihood of occurrence and the impact on project objectives. A total of 103 participants took part in this survey from all over the world. However, the data from 92 mining professionals from developing countries were utilized.

2.3 Development of a fuzzy rule based risk assessment model

A fuzzy set may be defined as a collection of elements in an information universe whose boundary is ambiguous, vague, or otherwise fuzzy. A membership function specifies each fuzzy set, assigning a value within the unit interval [0, 1] to each element in the universe of discourse (Wang and Elhag, 2007). An element can belong to a set fully, partially, or not at all. There are three possible belonging scenarios (Zadeh, 1965):

1. $\mu_A(x) = 1$; the element is fully a member of fuzzy set A,
2. $\mu_A(x) = 0$; the element is not a member of fuzzy set A,
3. $0 < \mu_A(x) < 1$; the element belongs only partially to fuzzy set A.

The proposed risk assessment model is described in the following steps.

2.3.1 Selection of the fuzzy inference system

The first step in developing the risk assessment model is choosing a fuzzy inference system, which generates a mapping between the inputs and output variables. MATLAB Fuzzy Logic

Toolbox provides the option to choose between two types of fuzzy inference systems: Mamdani and Sugeno. Table 1 compares both types of fuzzy inference systems. We used Mamdani Fuzzy Logic for this research due to its intuitive nature and ease of application.

Table 1. Advantages of each type of fuzzy inference system.

Fuzzy Inference System	Traits
Mamdani	Intuitive
	Well-suited to human input
	More interpretable rule base
	Have widespread acceptance
Sugeno	Computationally efficient
	Work well with linear techniques
	Work well with optimization and adaptive techniques
	Guarantee output surface continuity
	Well-suited to mathematical analysis

2.3.2 Definition of the linguistic variables

The second step is defining the linguistic variables of the risk assessment model designed in this study. A linguistic variable is defined as a variable that can take words as its value in natural languages, where words are represented by fuzzy sets defined in the universe of discourse in which the variable is defined (Zeng et al., 2007).

The model consists of two input variables: the *likelihood of the risk occurrence* and the *impact of the risk on project objectives*. Calculations based on these input variables provide an output variable: the relevance of the risk in sustainable mining operations.

2.3.3 Incorporation of the professionals' evaluations into a one fuzzy single value

The third step aggregates the respondents' assessments into a single fuzzy value for each of the input variables identified for each risk. To achieve the single fuzzy value, the fuzzy weighted trapezoidal average is used Eq. (1).

$$\overline{X} = \frac{\sum_{j=1}^{j=92} X_j \text{ x } W_{jk}}{\sum_{k=1}^{k=5} W_{jk}} \qquad (1)$$

In Eq. (1), $\overline{X}$ is the fuzzy single value which incorporates all the evaluations $(X_1, X_2, \ldots X_{92})$ of the respondents $(R_1, R_2, \ldots R_{92})$ for each input variable (the likelihood of occurrence and the impact on project objectives) for each risk. The symbol x denotes the fuzzy multiplication operator, whereas $(w_1, w_2, \ldots w_5)$ demonstrate the weights assigned to the respondents' assessments based on their professional experience. The different weights applied according to the years of respondents' experience appear in Table 2.

Table 2. Weights applied according to the years of respondents' experience.

Work experience	Weight
Less than 5 years ($\mathbf{w_1}$)	0.10
Between 5 - 10 years ($\mathbf{w_2}$)	0.15
Between 10 - 15 years ($\mathbf{w_3}$)	0.20
Between 15 - 20 years ($\mathbf{w_4}$)	0.25
More than 20 years ($\mathbf{w_5}$)	0.30

The final fuzzy single values obtained by incorporating the evaluations made by the respondents are shown in Table 3.

Table 3. Aggregated fuzzy values.

Group	ID	Risk	Likelihood	Impact
Economic and financial (EF)	EF-1	Commodity price variation and inflation	3.45	3.82
	EF-2	Lack or loss of investment	3.41	3.74
	EF-3	Cost of compensations emanating from liabilities	3.71	3.66
	EF-4	Changes in operating cost structure	3.39	3.61
	EF-5	Declining capital sources	3.34	3.43
Environmental and climate (EC)	EC-1	Air pollution	3.43	3.33
	EC-2	Emission burden	3.37	3.37
	EC-3	Land degradation	3.56	3.44
	EC-4	Problems in mine closure and reclamation	3.59	3.56
	EC-5	Waste generation	3.64	3.59
	EC-6	Water pollution	3.67	3.65
Health and safety (HS)	HS-1	Ergonomics associated risks	2.87	2.98
	HS-2	Inadequate protective equipment	2.74	3.19
	HS-3	Lack of health and safety management system	3.08	3.54
	HS-4	Lack of safety awareness among decision-makers	3.14	3.46
	HS-5	Mine hazards	3.38	3.71
Managerial (MG)	MG-1	Incompatible organizational/institutional structure	3.26	3.4
	MG-2	Labor disputes, strikes, or boycotts	2.87	3.14
	MG-3	Lack of employees' training	3.11	3.4
	MG-4	Recruitment and retention of skilled employees	3.21	3.33
	MG-5	Lack of sustainability measures at project start-up	3.29	3.59
Political and legal (PL)	PL-1	Compliance risk	3.24	3.25
	PL-2	Disputes and conflicts	3.13	3.34
	PL-3	Bureaucratic delays and complicated procedures	3.52	3.64
	PL-4	Political involvement	3.63	3.66
	PL-5	Regulatory risks	3.57	3.58

Social (SL)	SL-1	Claims arising from society	3.49	3.64
	SL-2	Displacement of communities	3.29	3.44
	SL-3	Disruption of local cultural heritage	3.19	3.4
	SL-4	Public opposition	3.33	3.58
	SL-5	Safety of local communities	3.22	3.55
Technical and operational (TO)	TO-1	Complex geological conditions	3.18	3.43
	TO-2	Errors in management and planning decisions	3.35	3.67
	TO-3	Errors in mine design and engineering processes	3.26	3.71
	TO-4	Geotechnical risks	3.34	3.57
	TO-5	Improper resource allocation and management	3.05	3.58
	TO-6	Inadequate geological prospecting	3.18	3.55
	TO-7	Incorrect mineral resource calculation	3.11	3.76
	TO-8	Limitation of equipment and technology	3.11	3.67

2.3.4 Determination of fuzzy membership functions

The fourth step is the formulation of fuzzy membership functions. A fuzzy membership function is a curve that represents the mapping of the input data points to a membership value or degree that has an interval between 0 and 1. Several types of membership functions are used on the Mamdani fuzzy inference system, some of which are triangular, trapezoidal, singleton, sigmoid, and Gaussian (Harliana and Rahim, 2017).

In this study, each linguistic variable is composed of five fuzzy sets. Each fuzzy set is described by a linguistic term. Consequently, five linguistic terms are used for the expression of each linguistic variable: “Very Low (VL)”, “Low (L)”, “Moderate (M)”, “High (H)”, and “Very High (VH)”. There are several membership functions, including triangular, trapezoidal, and Gaussian. The trapezoidal functions were chosen in this study because their formula is straightforward, and they are computationally efficient. This membership function employed for the expressions above is defined in Fig. 5.

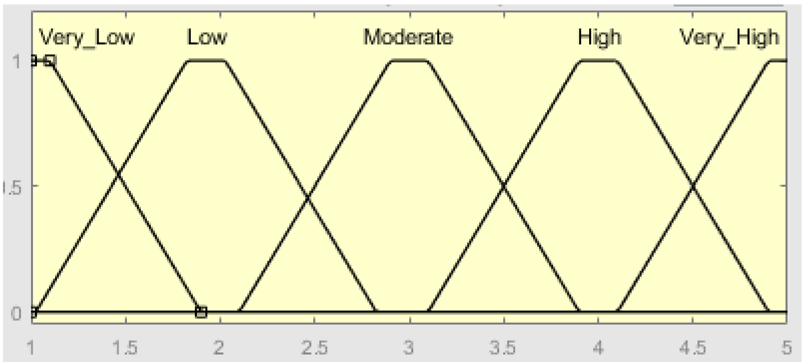


Fig. 5. The fuzzy definition of the linguistic variables.

Each fuzzy set of the variables is defined with trapezoidal membership function (Fig. 6) given by Eq. (2), when $a < b < c < d$.

$$\mu_A(x) = \begin{cases} 0, & \text{if } x < a \\ \frac{x-a}{b-a}, & \text{if } a \leq x \leq b \\ 1, & \text{if } b \leq x \leq c \\ \frac{d-x}{d-c}, & \text{if } c \leq x \leq d \\ 0, & \text{if } x > d \end{cases} \tag{2}$$

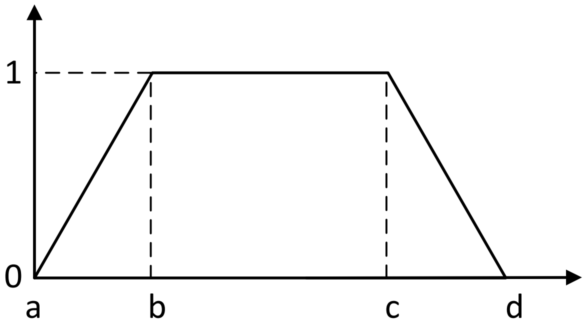


Fig. 6. Trapezoidal membership function representation.

The linguistic terms for two input variables (the likelihood of occurrence and the impact on project objectives) and one output variable (the relevance of the risk in sustainable mining operations) can be described as shown in Table 4.

Table 4. Linguistic terms and trapezoidal fuzzy numbers for each variable.

Variable	**Linguistic term**	**General interpretation**	**Trapezoidal fuzzy number**
Likelihood	Rare	The risk is very unlikely to occur	(1.0 1.0 1.1 1.9)
	Unlikely	The risk is unlikely to occur	(1.1 1.9 2.1 2.9)
	Moderate	There is a certain likelihood that the risk will occur	(2.1 2.9 3.1 3.9)
	Likely	The risk is likely to occur	(3.1 3.9 4.1 4.9)
	Almost certain	The risk is very likely to occur	(4.1 4.9 5.0 5.0)
Impact	Negligible	The risk impact is very low.	(1.0 1.0 1.1 1.9)
	Minor	The risk impact is low.	(1.1 1.9 2.1 2.9)
	Moderate	The risk impact is moderate.	(2.1 2.9 3.1 3.9)
	Major	The risk impact is high.	(3.1 3.9 4.1 4.9)
	Severe	The risk impact is very high.	(4.1 4.9 5.0 5.0)
Relevance	Minimum	The risk relevance is minimal, no management actions are required.	(1.0 1.0 1.1 1.9)
	Low	The risk relevance is low, specific management actions may be required.	(1.1 1.9 2.1 2.9)
	Moderate	The risk relevance is of medium level, management actions are required.	(2.1 2.9 3.1 3.9)

	High	The risk relevance is substantial, response strategies and monitoring are required.	(3.1 3.9 4.1 4.9)
	Extreme	The risk is a priority; specific response strategies and monitoring are required.	(4.1 4.9 5.0 5.0)

2.3.5 Fuzzification

Fuzzification (Fig. 7) is the fifth step, which involves transforming crisp inputs into fuzzy inputs with the assistance and support of the previous membership functions.

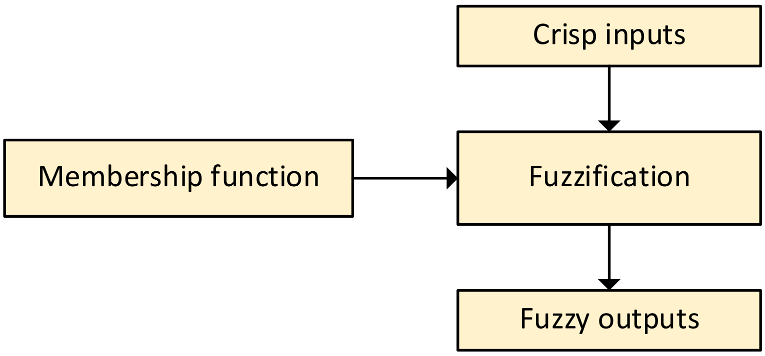


Fig. 7. Stages of Fuzzification

2.3.6 Selection of fuzzy If-Then rules

The sixth step is the selection of fuzzy If-Then rules (Fig. 8). In a fuzzy inference system, a fuzzy If-Then rule is of the form:

If x is A, then y is B,

where A and B are linguistic values defined by fuzzy sets on universes of discourse X and Y, respectively. The expression “x is A” is called the premise or the antecedent, while “y is B” is called the consequence or conclusion (Yen, 1999).

In this study, a total of 25 If-Then rules (Fig. 9) were established to explain the relationship between the processed input variables (the likelihood and the impact on project objectives) and the output variable (relevance in project management for sustainable mining operation) (Moreno-Cabezali and Fernandez-Crehuet, 2020).

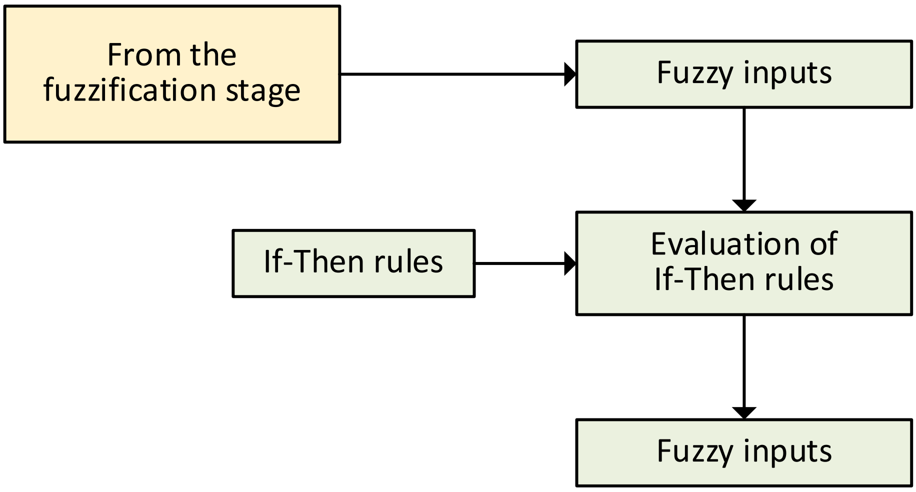
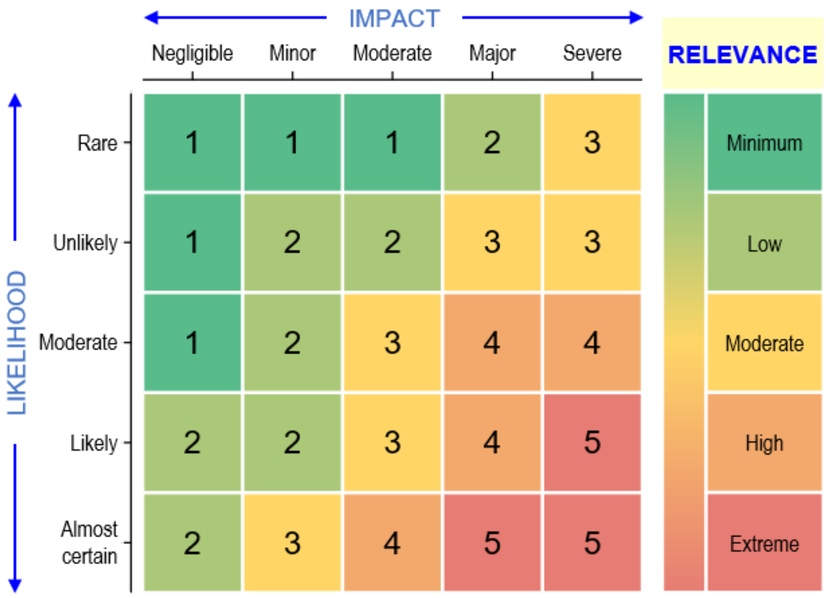


Fig. 8. Stages of the Evaluation of the If-Then rules



	Negligible	Minor	Moderate	Major	Severe
Rare	1	1	1	2	3
Unlikely	1	2	2	3	3
Moderate	1	2	3	4	4
Likely	2	2	3	4	5
Almost certain	2	3	4	5	5

Fig. 9. Fuzzy If-Then rules.

2.3.7 Defuzzification

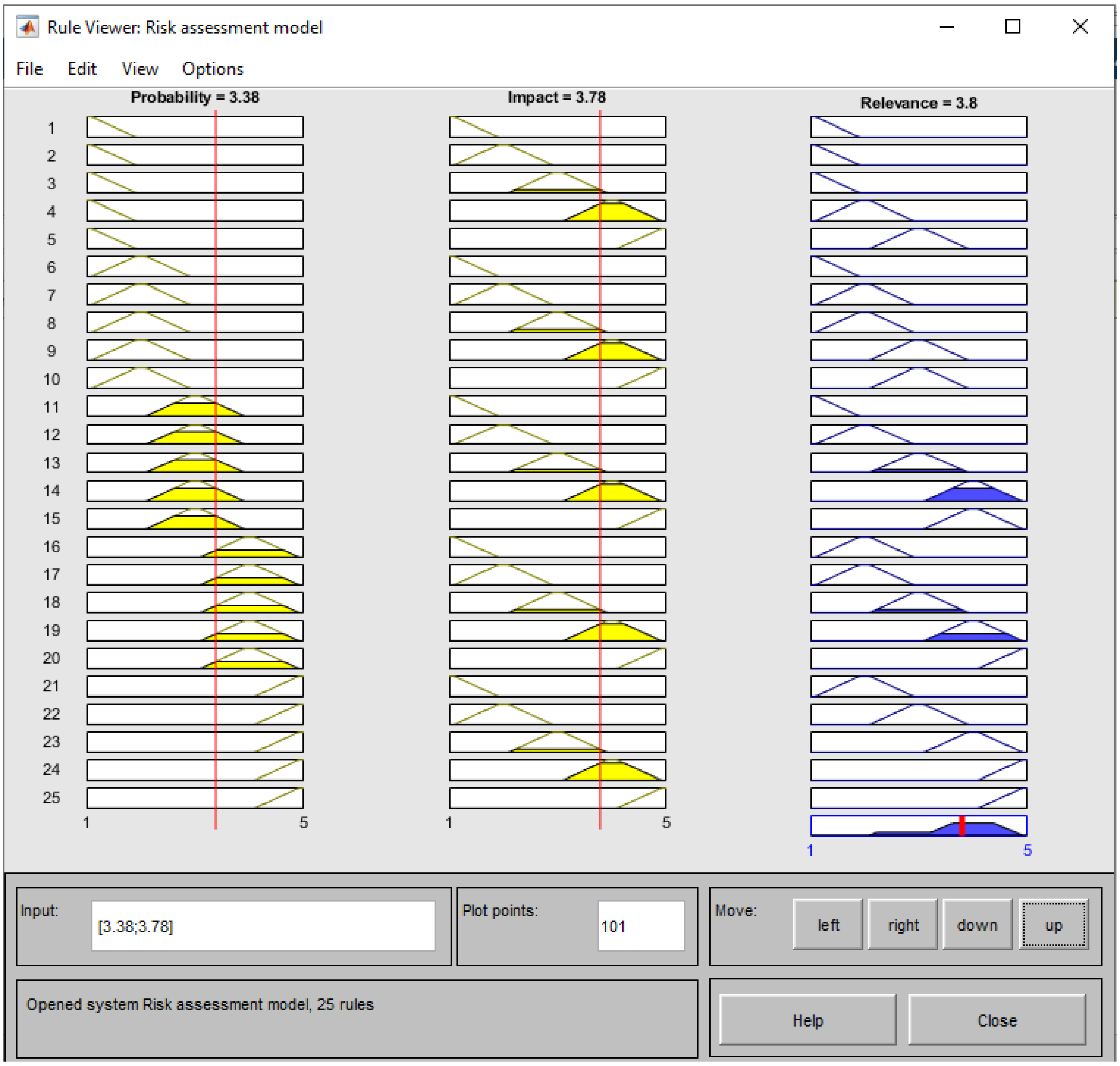
Defuzzification is defined as the process of converting the fuzzy outputs to crisp outputs as an effect of the numeric crisp inputs' values. A crisp numerical value relates to the support of the single fuzzy output set (Bobyr et al., 2017).

Because different methods are available, such a transformation is not unique. Some are the weighted average method, centroid defuzzification method, or singleton. The centroid defuzzification method has been chosen in this research, which is the most common. It is also known as the name center of gravity or center of defuzzification of the area.

This method returns the center of gravity of the fuzzy set along the x-axis. The centroid is the point along the x-axis about which the fuzzy set would balance. The centroid is computed using the following formula Eq. (3), where $\mu(x_i)$ is the membership value for point x_i in the universe of discourse.

$$xCentroid = \frac{\sum_i \mu(x_i)x_i}{\sum_i \mu(x_i)} \tag{3}$$

Finally, the software produces crisp outputs, as shown in Fig. 10. Each crisp output is the level of relevance that each risk has for a given likelihood and impact level.



Input: [3.38;3.78]

Plot points: 101

Opened system Risk assessment model, 25 rules

Fig. 10. Rule Viewer

The algorithm of the program is greatly facilitated using *readfis*, *input,* and *evalfis* functions. In this case, the evaluation of multiple assessments of the input variables (Likelihood and

Impact) in the fuzzy inference system (FIS) established in this study is required to determine the final value of the relevance of each risk. The following steps were taken to accomplish this procedure:

- First, the FIS designed in this investigation is loaded, which has been developed in the methodology section. To do this, the *readfis* function is used as follows Eq. (4):

$$fis = readfis('Risk\ assessment\ model') \qquad (4)$$

- Second, the final evaluations of the experts corresponding to the Likelihood and Impact of each risk are incorporated. For each input variable, a matrix is used, A for Likelihood and B for impact. In this way, the input combinations are evaluated using an array, as indicated in Eq. (5).

$$input = [A\ B] \qquad (5)$$

- Third, the FIS is evaluated for the specified input combinations. To do this, the *evalfis* function is used.

$$out = evalfis(fis, input) \qquad (6)$$

3. Results and discussion

This research work analyzed and indexed thirty-nine risks associated with the disruption of a mining system designed to provide a constant supply of critical minerals. A risk evaluation model is proposed and implemented in MATLAB Fuzzy Logic Toolbox to quantitatively compute the risk relevance using two parameters: *likelihood of occurrence* and *impact on the project*. The relevance scores for each of the risks are presented in Table 5. The chronological ranking enables mines, mine managers, and decision makers to determine the overall risk relevance to sustainable mining operations in terms of the likelihood of occurrence for risk and its impact after the occurrence. These findings will aid the mining industry in performing due diligence regarding sustainable operations by planning beforehand about the prospective likelihood and impacts of the risks discussed in this work. The Supplementary Data, freely available to the public, includes assessments of each parameter of each risk (likelihood and impact), as well as the breakdown of risk relevance by country. Any reader interested in expanding their knowledge base can compare the different values corresponding to the two input variables, and the output variable for each risk, across 30 participating countries.

Table 5. Relevance scores and ranking of the risks.

ID	Risk	Likelihood	Impact	Relevance	Ranking
EF-1	Commodity price variation and inflation	3.45	3.82	3.84	1
TO-7	Incorrect mineral resource calculation	3.11	3.76	3.79	2
EF-2	Lack or loss of investment	3.41	3.74	3.74	3
TO-3	Errors in mine design and engineering processes	3.26	3.71	3.73	4
HS-5	Mine hazards	3.38	3.71	3.71	5
TO-2	Errors in management and planning decisions	3.35	3.67	3.68	6
TO-8	Limitation of equipment and technology	3.11	3.67	3.68	7
EF-3	Cost of compensations emanating from liabilities	3.71	3.66	3.67	8
EC-6	Water pollution	3.67	3.65	3.66	9
PL-4	Political involvement	3.63	3.66	3.66	10
EF-4	Changes in operating cost structure	3.39	3.61	3.62	11
PL-3	Bureaucratic delays and complicated procedures	3.52	3.64	3.61	12
SL-1	Claims arising from society	3.49	3.64	3.6	13
EC-5	Waste generation	3.64	3.59	3.59	14
MG-5	Lack of sustainability measures at project start-up	3.29	3.59	3.59	15
PL-5	Regulatory risks	3.57	3.58	3.58	16
SL-4	Public opposition	3.33	3.58	3.58	17
TO-5	Improper resource allocation and management	3.05	3.58	3.58	18
TO-4	Geotechnical risks	3.34	3.57	3.57	19
EC-4	Problems in mine closure and reclamation	3.59	3.56	3.56	20
SL-5	Safety of local communities	3.22	3.55	3.55	21
TO-6	Inadequate geological prospecting	3.18	3.55	3.55	22
HS-3	Lack of health and safety management system	3.08	3.54	3.54	23
HS-4	Lack of safety awareness among decision-makers	3.14	3.46	3.46	24
EC-3	Land degradation	3.56	3.44	3.44	25
SL-2	Displacement of communities	3.29	3.44	3.44	26
EF-5	Declining capital sources	3.34	3.43	3.43	27
TO-1	Complex geological conditions	3.18	3.43	3.43	28
MG-1	Incompatible organizational/institutional structure	3.26	3.4	3.39	29
MG-3	Lack of employees' training	3.11	3.4	3.39	30
SL-3	Disruption of local cultural heritage	3.19	3.4	3.39	31
EC-2	Emission burden	3.37	3.37	3.36	32
EC-1	Air pollution	3.43	3.33	3.35	33
PL-2	Disputes and conflicts	3.13	3.34	3.33	34
MG-4	Recruitment and retention of skilled employees	3.21	3.33	3.32	35
PL-1	Compliance risk	3.24	3.25	3.22	36
MG-2	Labor disputes, strikes, or boycotts	2.87	3.14	3.02	37
HS-1	Ergonomics associated risks	2.87	2.98	2.95	38
HS-2	Inadequate protective equipment	2.74	3.19	2.91	39

The ranking of the evaluated risks is an essential component that offers insights into the resources required to manage and mitigate high-probability and high-consequence risk events. However, in order to better prioritize them, risk categorization based on relevance scores can lead to appropriate decisions about which risks should receive higher priority for mitigation or management (Jiskani et al., 2020a). In order to properly determine priority levels, this study categorizes all evaluated risks into two priority levels: critical and important. For this purpose, the average of risk relevance scores was calculated (3.50). A risk with a relevance score equal to or greater than 3.50 is considered a critical priority risk, whereas a relevance score less than 3.50 indicates that the risk has an important priority. These two distinct category levels aid in identifying risks and dealing with them accordingly, which is beneficial in a number of ways. For instance, it provides a structured and focused approach to identifying the most critical risks, simplifies risk monitoring, and enables the development of more effective risk mitigation approaches and risk response strategies. Since different projects may entail a variety of risk sources, it is challenging to develop a one size fits all risk management plan. Therefore, risk categorization is particularly advantageous in this regard. The results indicate that the top 23rd ranked risks have a relevance score greater than 3.5, classifying them as critical priority risks. Among the 23 critical risks identified, 7 out of 8 are from the technical and operational group, and 4 out of 5 are from the economic and financial group. There are three risks from each of the two groups, political and legal, and social.

The analyses reveal that “commodity price variation and inflation” is the most critical risk with relevance to sustainable mining operations. Commodity prices and inflation are critical parameters in decision-making and policy formulation, and they sometimes result in early closure or reopening of mines. Thus, accurate price forecasting, mineral resource estimation, mineral resource disclosures, and the reliance of emerging technologies on the commodity being mined must be incorporated at the time of cost estimations. The results indicate that the impact of changes in commodity prices and inflation is usually greater than their respective likelihood of occurrence. It implies that respondents have higher confidence in current commodity prices and inflation estimates. However, they have identified that the impact of changes in prices and inflation will be the highest if occurred and is intuitive.

“Incorrect mineral resource calculation” obtained the 2nd rank in the analysis. With the advent of industry standards, such as NI-43-101, SK-1300, JORC, on mineral resource estimations and calculations, the possibility of an issue pertaining to incorrect or false mineral resource calculation is low. However, in the case of occurrence, the impact is deemed similar to the changes in commodity prices and inflation, i.e., greater than the likelihood of occurrence. Notably, inaccurate mineral resource calculations or estimations may lead to legal disputes or, in the worst-case scenario, the suspension or permanent closure of mining activities, rendering the mineral reserves with no prospect of economic value. The occurrence of such an event takes away the trust of investors, which can easily lead to a domino effect towards closure. This demonstrates a high level of impact, as well as the overall relevance of the risk to sustainable mining operations.

"Lack or loss of investment" is the 3rd most critical risk, resulting in similar outcomes as that of the previous two risks. Backing out of investors can emanate due to the occurrence of any of the risks in projects as it demonstrates incompetence on the part of the administration and technical staff. The impact of lack of investment is higher than errors in mine design and mine hazard occurrence, which appears to be logical. A mine might have money budgeted for safety improvements and hazardous maintenance at the start of the operation, but lack of investment to carry out mining operation will halt the mining activity and might require newer fund generation, which can severely affect sustainable operation. Securing investment and explaining to investors about the company's financial performance (Litvinenko and Sergeev, 2019) and communication about prospective of incidents occurrence can help mining companies gain the trust of investors, ensuring that they do not back out in case of uncertainty associated with mining activity.

The "errors in mine design and engineering processes", the 4th ranked risk, follows the same pattern as the majority of the risks in this analysis, i.e., the impact is greater than the likelihood. This is true as mine design and engineering processes have matured over the years and require relatively few newer interventions. However, bad designing practices, unsafe or non-engineered approaches, and cutting corners can result in errors in mine design and engineering processes related events, thus, impacting the sustainability of mining operations. Stricter regulations can result in stringent actions against the violations, which may impair the continuation of the mining operation. Thus, extra due diligence is needed during mine design and engineering processes execution.

The impact of "mine hazards" on the sustainability of mining operations is placed at 5th rank in terms of relevance. The findings indicate that respondents consider the likelihood of mine hazard occurring is less than the probability of fluctuations in commodity price and investment loss. It may be inferred that mine safety, being part of the mining operation system, can be controlled and improved, making it less likely to result in mine hazards. However, the occurrence of such an incident will have a severely detrimental impact on the sustainability of mining operations. This also might show the trust of respondents in the safety standards of their operation, as compared to the price regulatory financial side of their locality/origin.

The risk of "errors in management and planning decisions" is ranked 6th on the list, with a lower chance of occurrence. However, once it occurs, it may have a huge influence on the sustainability of mining projects. The managerial and planning decisions have become a vital component of the sustainable mining business agenda. Indeed, sustainable mining is emerging as a global priority, and leaders in mining have a stake in making sustainability-related decisions, as well as increased accountability for their actions. A prime example will be the resignation of Rio Tinto's executive following the destruction of sacred aboriginal sites in Australia underscores the value of managerial and planning decisions and their impact in case of occurrence. These events can have a long-term impact on a company's reputation, stocks, future investment acquisitions, and public perception, thereby jeopardizing the sustainability goals not only for that specific company but the overall mining community as well. The likelihood and impact of such risks demonstrate the critical nature of mature decision-making on the part of managers and planners in order to maintain the sustainability of mining operations.

"Limitation of equipment and technology" has 7th rank. It has relatively less likelihood of occurrence. However, in case of such an event, the impact will be very high. According to findings, respondents believe that a lack of equipment and technology has much less likelihood of occurrence than other risks in the critical priority range. The greater impact of this risk is commensurate to the fact that abrupt changes in technology and equipment may be problematic. The findings indicate that the adequacy and appropriateness of equipment and technology selection should be prioritized and planned in advance for the entire life of mine. Improper selection, wrong fuel type, and inefficient emission control systems can result in long-term losses, putting a heavy dent in the sustainable mining operation.

The "cost of compensations emanating from liabilities" obtained 8th rank in the analysis. Based on the results for this work, it has the highest likelihood of occurrence than all risks evaluated. The increased probability of this risk implies a certain behavior towards paying compensation for social, environmental, and climate damages. These compensations might include land acquisition, wildlife, habitat relocation, etc. Many mining entities take pride in their environment-friendliness. Nevertheless, the risk impacts sustainable mining in developing countries and requires extensive due diligence before the start of operation and devising plans for mitigating it throughout the various stages of life.

The likelihood of occurrence of the 9th ranked "water pollution" risk is higher than the majority of other risks, except for the cost of compensations. The envisaged impact due to water pollution shows a considerable influence on sustainable operation. This also hints at a trend among mining professionals towards intolerance for water pollution and its undeniable negative impacts. Even though a short-term mining project might not see the impacts, the long-term issues emanating from water pollution might be dreadful for the local inhabitants and wildlife habitat living downstream. This requires a dedicated effort from industry, academia, and regulatory bodies to educate professionals about the critical nature of water pollution and enable them to reduce the impact of mining on the overall fabric of the world.

"Political involvement" is always a nightmare for any operation and must be avoided as much as possible. This may be the reason due to which this risk is under the list of critical risks, listed as the 10th critical risk to sustainable mining operations. The likelihood and impact of political involvement are almost similar in higher positions. Therefore, it ranked tenth in the overall relevance to sustainable mining operations. The mining companies should maintain apolitical status to the maximum and associate their operation with good community engagement (Ur Rehman and Awuah-Offei, 2018). Effective community engagement can result as leverage against ill-motives of bad politicians and can help mines operate sustainably. Nonetheless, political involvement must be envisaged at the start of mining operations for the correct identification of key stakeholders (Que et al., 2019).

"Changes in operating cost structure" obtained the 11th rank. This risk can significantly impact mining projects and their operation's stability. The majority of mining projects in developing countries attempt to be at high altitudes of production to meet immediate or anticipated increases in mineral demand, which also entails greater capital expenditure and operational expenses. However, a sudden jump in expenditure indicates incompetence and creates a lack of trust. Even though mining projects in developing countries are particularly vulnerable to this sort of risk, owing to unanticipated price fluctuation, inaccurate ore body predictions, and technical difficulties inherent in the mining system. Therefore, the risk of changing operating cost structure may emerge as a result of many factors, including but not limited to the procedures and technologies used, as well as the overall mining efficiency. This expands the challenges to mine planners when deciding on the most cost-effective ways of production, which underlines the need to pursue cost-effective implementation strategies that minimize pricing uncertainty and the possibility of incurring excessive operating costs. The approach to incorporate this expected risk in feasibility study can help operations run smoothly.

"Bureaucratic delays and complicated procedures" is ranked as the 12th critical risk affecting sustainable mining operation. The rectification of this risk lies more towards public policymakers, and the mining industry can only opt for a passive approach. A good understanding of approval procedures, strong litigation expert teams, and study of previous grants can help companies operate with sustainability. However, the major player to ensure sustainable mining operation is the government in this case, which must ensure a level playing field for attracting investors all over the world and provide them with a chance to uplift the opportunity cost of mining districts.

"Claims arising from society" was found as the 13th ranked risk. It is indeed possible to occur, but the respondents deem its likelihood lesser than the anticipated impact. This hints at a trend of understanding in respondents about the occurrence of compensation claims, thus addressing them at a later stage. The impact of claims arising from social sustainability requirements may have a significant impact on the sustainability of the mining industry.

The likelihood of occurrence of "waste generation" during a mining operation is higher, whereas the impact on the sustainable operation is not among the highest. The overall rank of 14th shows that respondents feel waste generation is an integral part of mining operations and must be part of the plan before commencement of the operation. This can be achieved by having proper tailing dams, correct waste stockpile designs, etc. However, the likelihood of occurrence does show general acceptability of occurrence for waste during a mining operation.

"Lack of sustainability measures at project start-up" is a managerial risk that ranks 15th in the current analysis. This risk has a higher impact than its probability, implying that it is one of the limiting factors in achieving sustainability of mining operations. The incompetence of leadership and management results in the failure to include and explicit sustainability measures in their strategic plans. With various countries committing to net zero targets and many companies allocating budgets for environmental, social, and governance compliances, mean lack of sustainability measures at start-up are not merely a mistake or omission; it is a blunder and shows a lack of awareness among the decision makers. The ultimate achievement of sustainable mining falls into place when sustainability measures are integrated into the everyday operating procedures and culture of the organization. A variety of initiatives, such as green and climate-smart mining and intelligent and low carbon mining, are in place to incorporate sustainability principles into mining activities. Nonetheless, these initiatives have frequently been constrained by their narrow focus on a particular sustainability issue or complicated technocentric solutions. Integration of such measures takes longer due to the lack of understanding or acceptance in case of conflicts and a failure to integrate inputs from the multiple hierarchical levels. Thus, an effective sustainability incorporation system should be developed, continuously evaluated, and followed up, and resources should be made available to accomplish the purpose. In this regard, senior management approaches, through authoritative power and change efforts, could help to ensure and expedite the incorporation of sustainability measures and their implementation as well. For this purpose, it is necessary to recognize the drivers for fostering sustainability measures, the changes required and used in corporate systems, organizational policies, strategies, and structures. The approaches and functions involved in assisting with the integration of sustainability measures and the barriers encountered, and approaches that can be taken or are available to overcome them for transitioning to sustainable mining must be studied at the project start-up. Many of these issues can be addressed by changing the attitudes of stakeholders and systems and taking concerted, collaborative actions by governments, financial institutions, businesses, and other key stakeholders.

The impact of "regulatory risks" occurrence is higher than its likelihood based on the results, and combined relevance to sustainable mining operation puts it at a rank of 16th. There can be various regulatory risks that can impact the sustainable operation, and they usually emanate from mine operations carrying out work in the gray areas of permissible limits, the political association of mining company or lack of consideration for society and laws. Sometimes they are successful, and sometimes they are not. The regulatory associated risks can be minimized by clarity in rules and policies for regulations and continuous improvement towards sustainable mining by mining companies.

"Public opposition" is the 17th ranked risk, whose impact is higher once it occurs. To achieve the goal of shifting to clean and low-carbon technologies, a larger quantity and a broader range of natural resources are needed. Nonetheless, public opposition to mining is greater than ever, which makes the development of new mines challenging (Editorial, 2016). It implies that in developing countries, public trust in the mining industry is in peril, highlighting the need for trust-building between communities and mining enterprises. In this sense, sustainable mining management would be a prudent way forward. Trust-building activities require collaborative efforts of society, industry, and government to engage in a continuous dialogue that will result in relationship-building and trust (Lesser, 2021). Excellent corporate social responsibility, environmental, social, and governance compliance, and effective community engagement can help in mitigating this issue.

As seen from the results, the risk of “improper resource allocation and management” ranked 18th. Resource allocation and utilization are an integral part of any operation, and in mining activities, a lot of resources are at the disposal of a smaller number of people. Due to incompetency, corruption, short-sightedness, and lack of interest, there is a tendency to allocate improper budget and human resources to a specific unit. The lack of resources can cause a safety or health related risk due to over-stretching of resources. Such events have less likelihood of occurrence, but once occurred, they have a critical impact on the sustainability of the operation.

“Geotechnical risks” are common in mining activities, and that is why it has a higher likelihood of occurrence than many other risks, thus getting 19th rank in critical risks. Usually, mines do intensive studies on maintaining stable operations with regards to geotechnical activities. However, there is always a chance of occurrence. Reasonable due diligence can help mitigate the impact or even reduce the likelihood of occurrence for such an event. Improper resource and manpower allocation can result in geotechnical disasters like the Brumadinho dam failure.

The rankings in our study highlight that “problems in mine closure and reclamation” is the 20th critical risk. It clarifies that mine closures and reclamation are a very important aspect and must be planned beforehand. The mindset to ignore and delay reclamation of parts of mine that are mined and will not have future activity during the operation must change. Such mentality does help companies look better on profits for an individual fiscal year, but in the long term, they have accumulated work to do which due to inflation, older machinery becomes very costly, and companies not making enough money around closures sometimes do not leave mines as they have promised. A prudent way to resolving these issues will be having phase-wise reclamation and remediation plans in action during the mining operation.

The 21st ranked risk is “safety of local communities”. The safety of local communities is contingent upon corporate social responsibility and effective community engagement. It is an accepted phenomenon that mining comes with money and the overall opportunity cost of the area increases. An increase in opportunity cost means more people and a higher crime rate as compared to the previous status quo. The allocation of resources to local police, the establishment of local security systems for communities and the inclusion of their feedback and opinions in the development of safety plans are all feasible ways to solve this problem. Sometimes due to differences in demographics and cultures, a very effective technique somewhere else might not be as effective, and that requires good community engagement.

The “inadequate geological prospecting” is at 22nd level of critical risks. The lack of correct geological information, which comes after indepth geological prospecting, can have both short term and long term damages. The short term damages can be a lack of information or knowledge to provide investors interested in the project. However, long term damages can range from improper or wrong resource estimation, bad safety design for mine due to lack of information on fault zones etc. Such risks can lead to long term issues in public reporting of resources as well. Therefore, it is necessary that the learned team with resources spend sufficient time in the field to gather all relevant data for improving certainty in geological prospecting.

When looking at the 23 critical risks, “lack of health and safety management system” is last on the list. It has quite a less likelihood of occurrence based on the results, but if it happens, it will have a substantial influence on the sustainability of mining operations. It can be interpreted that the mining industry has a good safety awareness culture, and that culture ensures safety practices; thus, respondents feel confident that there is less chance of lack of safety and health management. However, the efficiency of that safety and health management system is beyond the scope of the discussion presented here. Nonetheless, it is an important risk for sustainable mining operations and must be ensured during any mining operation.

The risks ranging from 24 to 39 are categorized as important compared to risks in the first 23 rankings, which are critical. The segregation between important and critical risks is based on their relevance scores. As risks in the important category also have reasonable chances of occurrence, they will also have an impact on the mining projects. However, the relevance score below 3.5 shows the general acceptability towards the occurrence of these risks to cause issues for sustainable operation. Nevertheless, for sustainable mining operations in the future, guidance and educating operators must be an integral part of the operation from start-up to closing to minimize the general acceptability to these issues as their cost to sustainable mining operation can be as *lack of safety awareness among decision-makers*, *land degradation*, *displacement of communities*, *declining capital sources*, and *complex geological conditions* cause long-term damage to publicly traded companies. The results reveal the reliance and prioritization of risks by the mining industry for the sustainable mining operation. Even though the critical risks act as to make or break for the mines, it is essential for mines to put efforts into improving the important risks to achieve a sustainable mining system. This study helps decision makers, mine sustainability focus groups, policymakers in policy formulation regarding future green and climate-smart mining and its perspective implications along the go. This work ranks the risks in order of priority to be addressed for long-lasting and socially acceptable mining practices for cleaners and greener energy.

4. Conclusion

The transition of the power generation industry towards green energy means an exponential increase in demand for critical metals and minerals. This implies that the transition and sustainable power generating operations are dependent on a constant supply of these minerals and metals. Delays or stoppages due to any incident emanating from various risks affiliated with the mining industry can affect the mineral supply chain, followed by the supply chain of all dependent components, thus domino effect towards a failure and hindrance to achieving net-zero targets worldwide. Identification, prioritization, and future remediation plans for probable risks related to the mineral supply chain for cleaner energy production are very important and must be identified. This work analyses 39 different risks, characterized in seven major groups as economic and financial risks, environmental and climate, health and safety, management, political and legal, social, and technical and operational. This work uses Fuzzy Logic based methodology to identify and prioritize the probable risks associated with the mining project. Each risk is evaluated independently to be prioritized in chronological order based on its relevance, which is determined by its likelihood of occurrence and impact. In summary, the technical and operational risks and economic and financial risks take precedence over those related to political and legal, social, environmental and climate, health and safety, and managerial groups. The work presented in this paper can assist policymakers in developing and implementing policies, as well as providing direction to the mining industry in developing plans to address these risks beforehand and minimize the impact on the supply chain of critical minerals required for cleaner production. This risk assessment tool will enable the identification, evaluation, and management of risks associated with projects at each stage, from the start to the end of the project. Similarly, it will help managers finish projects successfully while meeting the four fundamentals of every project, i.e., scope, cost, time, and quality (Golden Triangle). To that end, this tool will. The application of various modern risk assessment methods provides an opportunity to reduce the number of errors, limits irrational activities through optimal selection and competent management decisions to ensure a sustainable supply of minerals to the world for a sustainable and greener earth.

Data availability

The results obtained for each parameter of each risk, as well as the relevance with respect to each of them, are presented in Supplementary Data. The data is segregated based on the countries in the study.

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