




Prioritisation of Environmental Improvement Projects in Deep-Level Mine Ventilation Systems

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Abstract

Deep-level underground mining costs in South Africa are continuously rising due to the increased depth at which gold is being mined, resulting in a rise in virgin rock temperature and an increase in cooling requirements. Therefore, mines must evaluate various ventilation and cooling optimisation projects required to be implemented throughout their life of mine (LOM). This study develops a method to identify and prioritise large capital expenditure (CAPEX) underground environmental improvement projects, to improve thermal comfort underground. The solution presents a ‘multi-criteria decision-making’ (MCDM) process, incorporating the ‘analytic hierarchy process’ (AHP) and the ‘technique for order performance by similarity to ideal solution’ (TOPSIS) into the method to provide for scientific decision-making. These projects are evaluated based on four criteria, namely project risk, the impact on the underground thermal comfort, cost, and implementation time. This study’s solution uses ventilation simulations to determine the impact of the projects on the underground environment. The identification and evaluation of an environmental improvement project to best suit the current economic climate, while improving underground conditions and decreasing the safety risk is an essential aspect of the solution developed in this study. The method was implemented on a mechanised deep-level underground mine and showed that surface refrigeration is the most suitable alternative, which was implemented at the case study mine as validation of the developed solution. The study proves that the MCDM method is an adequate solution to incorporate subjective criteria into the decision-making process, resulting in a scientific and structured approach to making significant and complex decisions.

Keywords Multi-criteria decision-making method (MCDM) · Deep-level underground mining · Analytic hierarchy process (AHP) · Environmental improvement · Project prioritisation · Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

1 Introduction

1.1 Background to Mining Project Selection

Peaking at a production output of 1000 tonnes of gold mined in 1970 [1], South Africa was one of the top gold producers globally but has since battled to remain in the top 10 gold-producing countries. The rising cost of gold mining, which can be attributed to rising electricity prices, increased labour costs, the age of operations, and increasing mining depth, is

considered one of the main reasons South Africa’s gold production is declining [2].

For sustainable gold mining, strategic capital spend is required to counter the drastic cost increases faced by the mining industry. A ‘flexible’ ventilation and cooling plan that introduces ventilation and cooling at different stages of mine exploration, that can absorb the changes and development in planning is often suggested; however, this is not the case at every mine [3]. Infrastructure deterioration and cost-cutting occur due to an increase in mining costs [4]. Many studies have been conducted on improving the ventilation system and selecting the most suitable solution for the respective operational mine [5–14]. Most of these studies focused on benefit–cost analysis to establish the most beneficial solution at the lowest cost.

Determining the benefit of a ventilation project is a complex task due to the dynamics and integrated nature of a

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deep-level underground mine. There is an increasing presence of modern simulation tools to assist in solving these dynamic and integrated ventilation systems [15, 16]. Ventilation and climate simulation models have been used countlessly in designing and predicting future ventilation systems [15–21].

Although the most effective methods are used to quantify the impact at the lowest cost, risk should be considered in the decision-making process, as safety is a main priority in the mining sector. Deciding which project should be implemented is crucial for maximising the economic benefit without compromising safety (both acute and chronic) [22, 23]. Several studies considered incorporating additional aspects, such as the risk factor that is difficult to quantify during the decision-making process, but were unable to do so as the decision is left open to bias [6, 9, 13, 14, 19, 20]. Multi-criteria decision-making (MCDM) methods have been used in many industries to assist decision-makers with multi-criteria decision-making [24–29]. Mining-related studies are contemplated in more detail in the remainder of this section.

MCDM methods assist in structuring a scientific decision-making process while achieving the most accurate results. MCDM methods can handle large amounts of data with different criteria during essential decision-making [30]. Yavuz [31] explained that MCDM problems consider only a single objective: choosing from a list of alternatives to identify which alternative is the best fit. In the mining sector, MCDM has been used many times during the decision-making process of mining method selection [22, 31–43].

1.2 Literature on Recent Advances in MCDM and Ventilation Optimisation

To better understand what has been done relating to MCDM methods in the mining industry and project evaluation of environmental improvement projects, the literature on underground mines was examined based on the following:

- A—Whether the study uses MCDM methods to solve a decision-making problem.
- B—Does the study evaluate projects’ impact on underground thermal conditions?
- C—Is environmental simulation software used to determine the project’s impact in the underground environment?

Table 1 Summarises all the latest literature on MCDM TOPSIS methods and project evaluation in the underground mining industry.

The literature study showed that only three studies touched on an aspect of underground ventilation in the MCDM process; Kluge’s [33] and Nourali’s [34] studies of underground mining method selection dedicated one criterion to how the mining method would impact the ventilation without detailed evaluation. Kursunoglu [35] used the MCDM method during a fan selection process. The impact of each fan on the methane build-up and air quantity

Table 1 Summary of the research literature review

Main author	Literature criteria			Reference nr.
	A	B	C	
Acuña, Baiden, Gruting, Jacobs			x	[6], [44]–[46]
Ali, Amorcho, Asr, Javanshargiv	TOPSIS			[24], [32], [47], [48]
Bascompta, Makay, Maré, Mathews, Nel, Samito, Krog, De Souza, Du Plessis, Du Plessis		x	x	[7], [10]–[15], [19], [20], [49]
Alpay, Kabwe, Yavuz	AHP & Yager			[36], [50], [51]
Cheng		x		[8]
Bogdanovic, Balusa, Wang	AHP & PROMETHEE			[39], [52], [53]
Ataei, Alpay, Yetkin, Wang, Ebrahimabadi, Ghazikalayeh, Gupta, Jamshidi, Kazakidis, Kizil, Kluge, Kursunoglu, Musingwini, Owusu-Mensah, Özfirat, Peskens, Yavuz, Yavuz	AHP			[22], [23], [33], [35], [38], [54]–[66]
Ibishi	AHP & FMADM			[67]
Nourali	HPVS & DEA			[34]
Bitarafan, Karadogan	Fuzzy			[68], [69]
Hayati	VIKOR			[41]
Hudej	PROMETHEE, AHP, ELECTRE, VIKOR			[42]
Iphar	TOPSIS, VIKOR, ELECTRE, FMADM and PROMETHEE			[43]

was calculated using first principle calculations, which did not consider the whole integrated ventilation system of an underground mine.

Although MCDM methods are widely used in the mining industry, they were not previously used to evaluate the holistic ventilation and cooling system during the project selection process. MCDM methods have not been combined with ventilation simulations to determine the impact on the complete and integrated ventilation system. The literature highlighted a need for a method to assist decision-makers of deep-level underground mines in identifying various environmental improvement projects. In addition, a scientific decision-making method is required to prioritise these projects during the pre-feasibility stage.

1.3 Problem Statement and Objectives

This study aims to develop a method that can be used to identify large CAPEX environmental improvement projects in operational deep-level underground mines. After various projects are identified, they are prioritised using an MCDM process. Ventilation simulations will be incorporated to evaluate the impact of each project on a complex underground ventilation system. In the sections below, projects will be referred to as alternatives as this conforms to the naming convention used for MCDM methods. The development of the method will be discussed in the following section, followed by the implementation of the method at a case study mine.

2 Development of a New Prioritising Method for Environmental Improvement Projects

The method developed in this section will assist the mine in identifying improvement alternatives and choosing an adequate alternative to improve the underground environmental conditions. Figure 1 shows the steps to identify and prioritise the alternatives and is discussed in more detail in the remainder of the section.

Various research studies were consulted to develop the proposed method that will satisfy the need of the study [70–72]. Step 1 considers different literature methods and resources to assist in identifying alternatives to improve the

underground environment, and research (dictated Step 2's evaluation criteria). The two MCDM methods used in this method are existing methods previously used in other fields.

2.1 Step 1: Identify alternatives

The method's first step, shown in Fig. 1, is to identify alternatives to improve the environmental conditions. This would involve understanding and analysing the current ventilation and cooling system [73]. Defining the boundary of the investigated area is crucial to understanding the systems. The boundary can be a level or a whole complex of multiple mines and is defined to ensure the focus area is correct [73, 74].

Once the boundary is defined, the design criteria should be set to ensure an acceptable working environment underground. The acceptable working environment underground is established from the regional requirement and corporate policies [17, 75]. In a deep-level mine, the ventilation requirements are based on removing heat from the working areas as it overpowers other contaminants, namely mineral dust and noxious gasses [76, 77]. Air cooling power (ACP) has been indicated as a reliable heat stress index because it considers both the wet-bulb temperature and the airflow velocity [20, 77, 78]. An ACP of 250–300 W/m² is used during the design phase to ensure adequate ventilation in the working areas [77–81].

As the focus area and the design criteria are set up, the analysis of the system starts by baselining the system to assess the current conditions in the underground environment [73, 82]. During this activity, all the information is collected from the respective mine, which includes the following:

- Main intakes and returns temperatures and velocities
- Temperature, velocities, air mass flow and barometric pressure of level intakes and returns
- Heat sources
- Cooling capacities

The mass balance of the air quantity entering and leaving the boundary at the desired locations is possible using the collected information [16]. After the main air intake is checked, the level entrances can be checked in more detail. The required quantities should fall within the design criteria

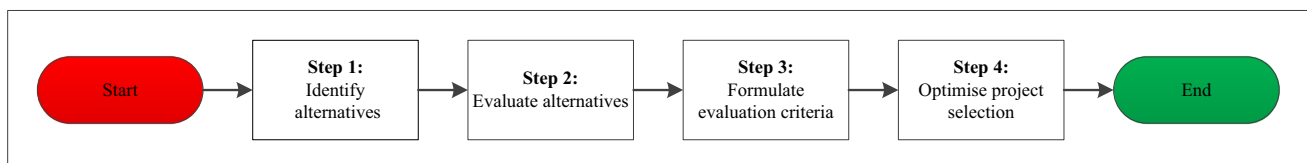


Fig. 1 New prioritising method for environmental improvement projects

defined earlier. The mass balance will highlight restricted airways, unintentional open areas, and total airflows.

The next step is to determine the heat load of the mine. A heat load study is used to determine if there is acceptable ventilation and cooling throughout the mine [72]. At this stage, the energy-balanced approach is used to determine all the heat sources and sinks, which can be best shown on a waterfall graph [72]. This will show how much cooling is needed to discard the air at the desired return temperature. After the evaluation of the system and possible problem areas have been established, solutions can be proposed.

Improvements can be either in the form of improving ventilation in the work areas or additional cooling. If inconsistencies were discovered during the mass balance, the possible solution would be ventilation-based, which can entail lowering the airway's frictional resistance, close-off or open areas [3]. Table 2 contains examples of solutions for the possible problems relating to ventilation.

The solution for a cooling shortfall during the heat load will be cooling-based and can be achieved by including additional cooling into the system. Table 3 contains examples of solutions for possible problems relating to cooling.

Using Tables 2 and 3 as a guideline, a list of possible alternatives can be compiled to improve the underground environment. During the next step, each alternative in this list will be evaluated.

2.2 Step 2: Evaluate alternatives

The second step in Fig. 1 is evaluating the environmental improvement alternatives list. The benefit–cost analysis only considers the project's benefits and implementation, but a good balance between safety and cost should be maintained in a physically hazardous underground environment [87]. The four criteria for evaluating the alternatives are risk mitigation ([13, 20, 87]), impact ([13, 19]), cost ([13, 19]), and implementation time.

The mine employees' safety is a top priority when assessing projects on the mine. Dehghani indicated that the results would be invalid if a project is evaluated without considering the risk of future losses [87]. Risk mitigation in this context refers to the impact that the implementation of the alternative will have to mitigate or divert a risk that may present itself in the future. The purpose of the risk management effort is to reduce the risk through a variety of site-specific means. A risk analysis is done to identify the extent of risks and is part of different aspects of the daily activities in the mining industry. Risk mitigation is difficult to incorporate during decision-making; nevertheless, a risk matrix is used to quantify risk mitigation value numerically [88, 89]. Dey's study incorporated a risk matrix to allocate a numerical value to a project's risk during project risk management [89]. Table 4 is an example of the risk matrix used during this study.

Table 2 Possible issues and examples of ventilation alternatives

Issue	Possible solutions	Explanation	Ref
Intake and return mass flows do not add up	Close sections	Close off abandoned areas	[83]
Not enough air supplied to the mine	Increase haulage size	Increasing the haulage size reduces a haulage's resistance and makes airflow easier	[84]
	New haulages (intake or return)	A new path of air to flow with less resistance in the airway to reduce the airflow and decrease friction resistance of the intake or return system	[3]
	Removing resistance	Deterioration of the airway increases the flow resistance. Remove unplanned waste, obsolete equipment, and fall of ground (FOG)	[77]
	Additional fans	Extend the reach of the existing ventilation network	[84]

Table 3 Possible issues and examples of cooling alternatives

Issue	Possible solution	Explanation	Ref
Cooling surplus but not cold in the working areas	Improve positional efficiency	Move cooling closer to the working area, so that there are fewer losses to the surroundings	[83]
Not enough cooling infrastructure	Surface cooling	Send cool air down the downcast shaft	[11]
	Send cold water from the surface underground	Pipe cold water underground for secondary cooling closer to the working areas	[85]
	Underground refrigeration	Cool water underground for underground bulk air cooler (BAC), operational water and tertiary cooling	[86]
	Ice from surface	Send ice underground in ultra-deep mines to use as cooling	[86]

Table 4 Example of a risk matrix (Adapted from [88])

Risk matrix		Consequences			
		1 System failure	2 Production loss	3 Legal liability	4 Close mine
Probability	4 Certain	4	8	12	16
	3 Likely	3	6	9	12
	2 Unlikely	2	4	6	8
	1 Rare	1	2	3	4

As shown in Table 4, the risk matrix will give a numerical value to the probability that something could go wrong and the possible consequences if it does. In this study, the probability is that if this alternative is not implemented, it may have severe consequences such as closing the mine. Tables 5 and 6 define probability and consequence, respectively.

The only way to thoroughly evaluate the complex deep-level mine ventilation system is through a simulation-based model [15, 19, 79, 90]. The simulation will be used to generate possible scenarios to determine the environmental impact of each alternative. The information collected during the baseline study is used to develop the simulation to imitate the existing ventilation system. As this is part of the pre-feasibility stage, only high-level calibration of the level entrances is necessary. The ACP change will be compared with the baseline value for the entrances, and an average value will

be used to express the proposed alternative’s impact on the underground environment.

In this economic climate, a cost analysis should be undertaken to ensure the alternatives are worth the costs [91]. Calculating each alternative’s net present value (NPV) will provide a reasonable capital and operational cost (CAPEX and OPEX cost) estimate. The cost analysis done during the pre-feasibility should be revisited during the final alternative plan [75]. Implementation time is selected as part of the criteria since a faster implementation time has a higher return on investment as production targets will be achieved more quickly. This will also assist in targeting ‘low-hanging fruit’ alternatives at the start. As this is still part of the pre-feasibility study, the time aspect is accurate in the range of ±30% [92].

The mine was analysed to understand the current underground conditions and identify suitable alternatives to

Table 5 Meaning of probability rows in risk matrix (Developed with [88])

No	Rating	Definition
1	Rare	The event is unlikely to happen
2	Unlikely	The possibility is slim that it can happen
3	Moderate	There is a likelihood that the accident can happen if the alternative is not implemented
4	Certain	The probability that the accident can happen is high and is a certainty if the alternative is not implemented

Table 6 Meaning of consequence column in risk matrix (Developed with [88])

No	Rating	Definition
1	System failure	The system may fail if the project is not implemented
2	Production loss	A lost blast is an undesirable effect if the alternative is not implemented
3	Legal liability	The possibility is that the Department of Mineral Resources and Energy (DMRE) can close the mine because it is not adhering to the legal requirements. Extensive work is required to fall within the design criteria
4	Close mine	If this alternative is not implemented, an event can lead to the closing of the mine. This could be based on the inability to reopen the mine due to high cost or hazardous environment

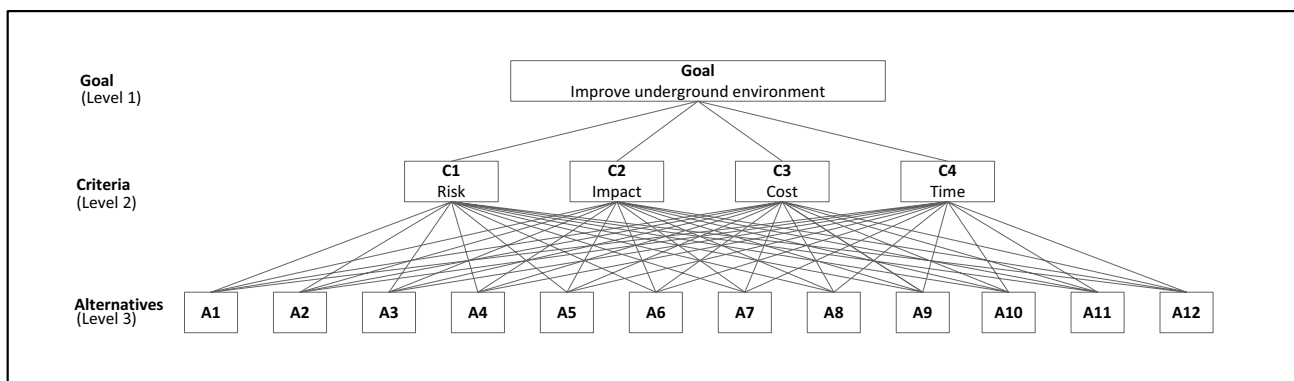


Fig. 2 Schematic framework of the AHP method

improve the environmental conditions. After the alternatives were identified, they were evaluated based on the preferred criteria. The steps described below use this information in conjunction with the MCDM tools to prioritise the alternatives.

2.3 Step 3: Formulate evaluation criteria

The analytic hierarchy approach (AHP) method can take a complex, multi-attribute problem and hierarchically structure it to solve an MCDM choice problem [70]. The AHP will be used to weight the criteria using a pairwise comparison.¹ Figure 2 is a schematic illustration of the AHP method used in this decision-making problem.

Level one in Fig. 2 is the goal of the MCDM method, which is to improve the underground environment with the most suitable alternative. Level two shows the criteria used to assess the alternatives, and level three is the alternatives that are compared to each other to choose the most suitable alternative to implementing. Table 7 shows the evaluation criteria’s symbol, nature of data, and attributes.

The criteria should be weighted according to the essential aspect of the decision-making method. In the case of an operational mine, risk mitigation and alternative impact should be on the same level because the benefit will lower the possibility of the risk occurring. Literature indicates that there should be a balance between financial return and safety [20, 21]. The cost of the alternative should not hinder implementation since it will mitigate the risk and improve the underground environment. Implementation time should not take superiority above any of the other criteria.

A pairwise comparison matrix or judgement matrix needs to be constructed, where the different criteria are weighted

in the $n \times n$ matrix. Equation 1 shows the construction of a judgement matrix [70].

$$A = \begin{matrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{matrix} \begin{bmatrix} C_1 & C_2 & C_3 & \dots & C_n \\ 1 & a_{12} & a_{13} & \dots & a_{1n} \\ a_{21} & 1 & a_{23} & \dots & a_{2n} \\ a_{31} & a_{32} & 1 & \dots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \dots & 1 \end{bmatrix} \tag{1}$$

where

- a_{ij} matrix element
- C criteria

In Eq. 1, the judgement matrix, A , shows the relative importance, a_{ij} , between the criteria, C_i , concerning the criteria, C_j . After the judgement matrix is set up, it should be normalised. Equation 2 is then used to calculate the relative weights (w_i).

$$w_i = \frac{\sum_{j=1}^n \bar{a}_{ij}}{n}, j = 1, 2, \dots, n \tag{2}$$

where.

- w_i relative weights
- \bar{a}_{ij} normalised element

Table 7 Evaluation criteria

Symbol	Criteria	Measurement	Goal (min or max)
C1	Risk	Qualitative (subjective)	Max
C2	Impact	Quantitative (objective)	Max
C3	Cost	Quantitative (objective)	Min
C4	Time	Quantitative (objective)	Min

¹ Pairwise comparison—compare criteria in pair to determine preference between each other [24]

Thus, $W = [w_1 w_2 \dots w_n]$ is the criteria weight vector. Next, judgement consistency (consistency control) should be performed to ensure the judgement matrix is acceptable and reasonable [93]. A consistency ratio (CR) of less than 10% indicates that the error in judgement is acceptable; if it is more than 10%, the criteria weighting method needs to be redone [94]. To calculate the consistency ratio, the consistency vector is calculated using Eq. 3.

$$[CV] = [A] \cdot [W] \tag{3}$$

Using Eq. 4, the eigenvalue of the consistency vector is then calculated.

$$\lambda_i = \frac{cv_i}{w_i}, i = 1, 2, \dots, n \tag{4}$$

where,

λ_i eigenvalue
 cv_i consistency element

The highest eigenvalue is calculated using Eq. 5.

$$\lambda_{max} = \frac{\sum_{i=1}^n \lambda_i}{n}, i = 1, 2, \dots, n \tag{5}$$

Using λ_{max} the consistency index (CI) can be calculated with Eq. 6.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

The last calculation to complete the consistency control calculation is to compute the consistency ratio (CR). Equation 7 is used to calculate the CR.

$$CR = \frac{CI}{RI} \tag{7}$$

where RI is the average random index value obtained using the order of the judgement matrix, which is 0.9, in this case. Equation 8 in the decision matrix (R) is used in the next step.

$$R = \begin{matrix} A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_n \end{matrix} \begin{matrix} Risk \\ Impact \\ Cost \\ Time \end{matrix} \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ x_{31} & x_{32} & x_{33} & x_{34} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & x_{n3} & x_{n4} \end{bmatrix} \tag{8}$$

In the next step, the alternative will be prioritised.

2.4 Step 4: Optimise alternative selection

The MCDM method used to optimise the alternative selection is the ‘technique for order preference by similarity to

ideal solution’ (TOPSIS) method. The TOPSIS method calculated the shortest distance, in a geometrical sense, to the ideal solution to determine the most suitable alternative [25].

The TOPSIS method was preferred to prioritise because of the rational and transparent nature of the method [71]. The advantage of the TOPSIS method above the other MCDM methods is that it calculates the best alternative in the shortest amount of time [95]. The TOPSIS method’s user-friendliness and high simplicity improve the interaction of the shareholders and decision-makers that do not have a technical background, with the method [24].

The TOPSIS method is practically used to prioritise the alternatives from the most suitable to the least suitable for improvement [24, 96].

Using the TOPSIS method, the first step is calculating the weighted normalised matrix. Equation 9 is used to calculate the weighted normalised matrix.

$$V_{ij} = W_i \times \bar{R}_{ij} \tag{9}$$

The weighted normalised matrix is calculated by multiplying the normalised decision matrix columns by the weight of that column’s criteria. The geometrical distance, Euclidean distance, to the ideal solution should be determined next. The attributes listed in Table 7 above are used to determine each column’s ranges. A high range, maximum value, is favoured for impact and risk, while a low range, minimum value, is favoured for cost and time. Now, the positive ideal solution (PIS) can be identified using Eq. 10 and the negative ideal solution (NIS) using Eq. 11 [25].

$$V^* = \{v^*_1, v^*_2 \dots v^*_n\} = \{(\max_j v_{ij} | i \in I'), (\min_j v_{ij} | i \in I'')\} \tag{10}$$

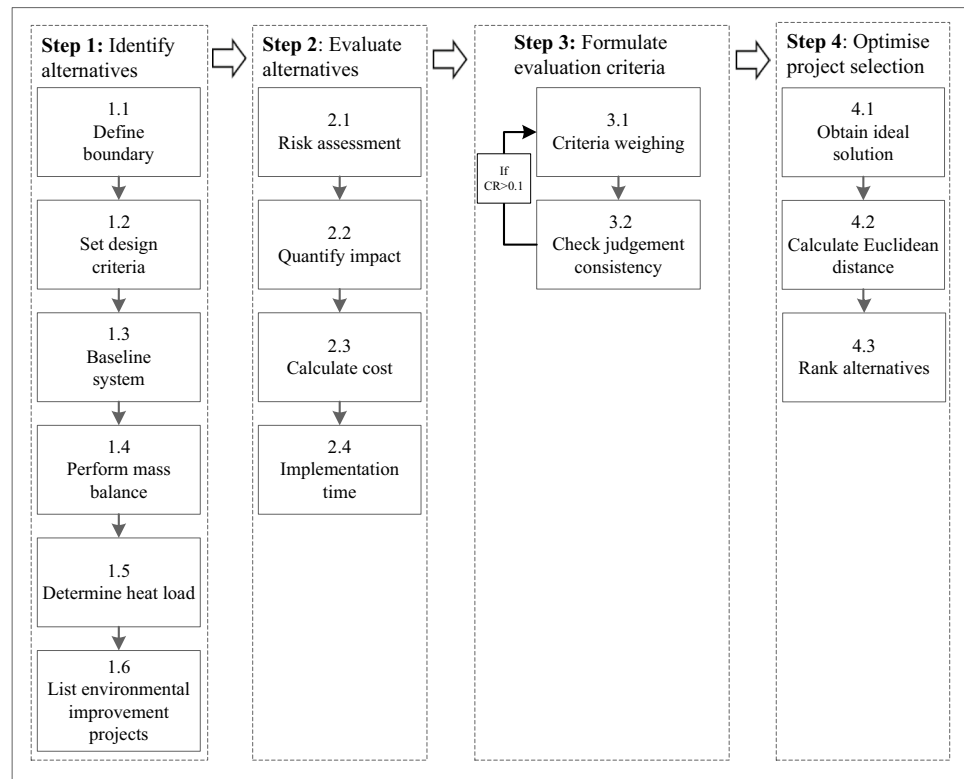
$$V^- = \{v^-_1, v^-_2 \dots v^-_n\} = \{(\min_j v_{ij} | i \in I'), (\max_j v_{ij} | i \in I'')\} \tag{11}$$

In Eq. 10, the highest value of that column must be added to the V^* list for the maximum attributes while the lowest value is used for the minimum attribute. In Eq. 11, the smallest value for the maximum attributes and the highest value for the minimum attribute must be added to the V^- list. The distances to the ideal solution can now be quantified using Eq. 12 for the Euclidean distance to the PIS and Eq. 13 for the Euclidean distance to the NIS [47].

$$D_i^* = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^*)^2}, i = 1, 2, \dots, j \tag{12}$$

$$D_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}, i = 1, 2, \dots, j \tag{13}$$

Fig. 3 Proposed method to identify and prioritise alternatives



The last step is to prioritise each alternative to the ideal solution. Equation 14 is used to calculate the relative closeness [97].

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-}, j = 1, 2, \dots, n \quad (14)$$

Equation 14 will prioritise the alternatives in decreasing order.

The proposed method in Fig. 1 can be extended into more sub-steps as described above. Figure 3 shows the extended proposed method with the sub-steps per step.

The proposed method is applicable for brown-field deep-level underground mines which do not have acceptable environmental working conditions. The following section will apply the proposed method to a case study.

3 Application and Results

3.1 Case Study Background

An operational gold mine in South Africa has difficulty keeping the ventilation in the underground environment to acceptable working standards due to shortcuts and cost-cutting while striving for the highest production yield. The mine has two intakes and one return airway up to 2300 m

underground. A decline connects the shaft, 6 km further, to the mining area. The mining method is a combination of conventional narrow reef- and mechanised trackless -mining. Figure 4 shows a schematic illustration of the mine.

The life of mine (LOM) is calculated to be 7 years, and interventions are needed to ensure a safe working environment is created to extend the mine's operational life.

3.2 Application of Proposed Method

The implementation of the developed method in the case study mine will be discussed in this section.

Step 1 in Fig. 5, identifies different alternatives to be implemented to improve the underground environment, which will start with setting the boundary and the design criteria. The boundary is presented by the red line in Fig. 4 which includes the intake airways, return airways, and the whole mining block. As the mine operates diesel machinery, additional airflow design criteria are necessary for the diesel particular matter (DPM). Table 8 shows the design criteria for this specific mine.

As the design criteria are set, the current underground information should be collected and act as the baseline to determine whether the alternative will have an impact. Table 9 indicates the current airflow and temperature information for the measuring points in Fig. 4.

Fig. 4 Schematic illustration of the case study mine

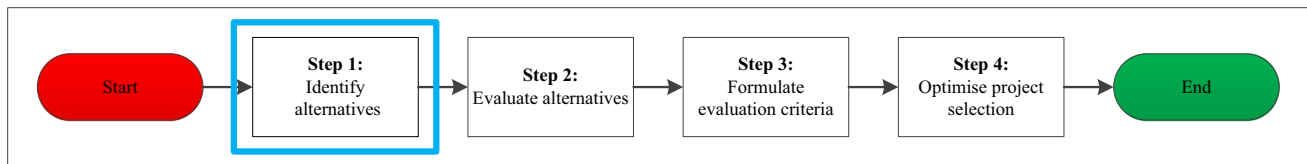
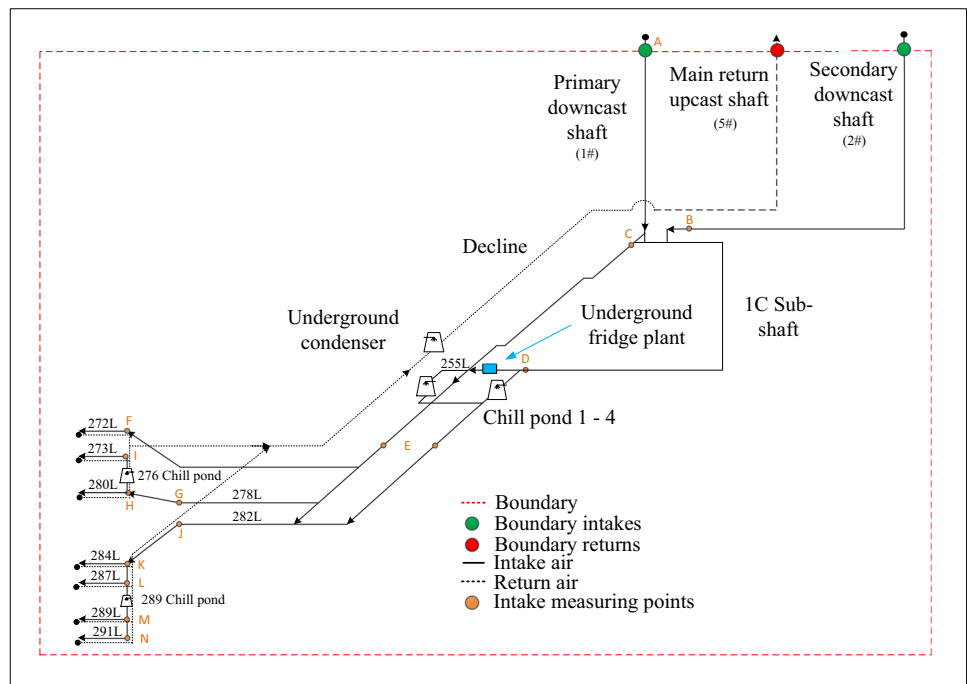


Fig. 5 Step 1 of the method - Identify alternatives

Table 8 Mine design criteria

Description	Value
ACP (kW/m ²)	300
DPM ventilation requirement (kg/s per rated kW)	0.06
Main return temperature (°C)	29.5

There is no refrigeration on the surface, and chilled water for cooling and mining comes from the refrigeration system located on 255L. Water is piped down to the mining block, which supplies two chill ponds, mobile cooling units and drilling water. Table 10 provides the refrigeration circuit information.

The mass balance over the intakes and returns can now be done. While busy with the mass balance, one of the design criteria can also be verified, namely the required airflow quantity based on the diesel machinery. The rated power of the diesel machinery is 15,000 kW while using a utilisation factor of 35% gives a rated power of the diesel machinery as

5250 kW [98]. Table 8 above shows the value of 0.06 kg/s per rated power, giving an intake airflow of 315 kg/s. Figure 6 shows the locations where the mass balance is done.

At the locations shown in Fig. 6, the mass balance is presented in Table 11.

Table 11 shows a difference between the intake and returns due to leaks and restrictions. Another big difference is between the intake A-A and B-B and the returns at both points. An airflow mass flow of 315 kg/s is needed for the mining block, where both these locations deliver less than the required quantity. The first cause of action should be to fix all the leaks in the system. Should this option be exhausted, alternatives related to the increasing flow capacity should be investigated. The next action is determining whether the mine has enough cooling infrastructure in place by performing a heat load study. Figure 7 graphically shows all the heat sources and heat sinks in the mine.

In Fig. 7, the baseline shortfall of 3970 kW, calculated through the energy-balance approach, is due to the current mine return temperature being higher than 29.5 °C. Assuming the mining method remain unchanged, the heat load was

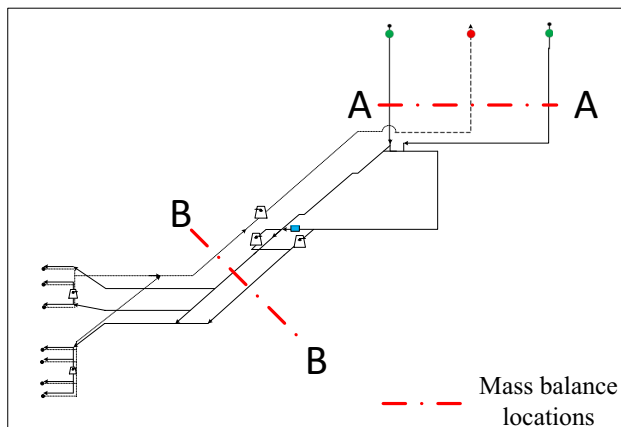
Table 9 Mine intake flows and temperatures

Ref. (Fig. 4)	Level	Intake				
		Mass flow (kg/s)	Velocity (m/s)	Wet-bulb temp (°C)	Dry-bulb temp (°C)	ACP (kW/m ²)
A	Surface	236.8	5.4	20.0	28.0	1 283.8
B	2# ²	42.2	4.1	27.6	30.4	646.3
C	50L	183.1	5.5	25.8	33.5	839.5
D	255 (1C#)	54.5	4.5	35.0	38.5	108.5
E	MB intake	230.1	4.2	25.2	26.4	827.0
F	272	28.4	0.9	26.4	29.7	490.5
G	278	45.4	0.8	26.7	29.8	377.0
H	280	23.4	0.7	28.8	31.5	353.1
I	273	12.1	0.4	29.7	30.5	256.6
J	282	147.7	1.6	28.8	30.0	436.6
K	284	37.0	1.2	29.5	31.8	370.0
L	287	53.3	1.0	32.8	32.3	181.4
M	289	12.5	0.2	29.9	31.8	205.5
N	291	60.7	0.8	32.9	35.4	185.5

= Shaft.

Table 10 Mine's refrigeration and water information

Description	Value
Current cooling duty (kW)	10,129
Plant utilisation (%)	73
Cold dam temperature (°C)	15
Avg. MB water usage (ℓ/s)	110

**Fig. 6** Locations of the mass balance for the mine**Table 11** Mine's mass balance

Ref	Level	Intake (kg/s)	Return (kg/s)	Difference (%)
A-A	Vertical shafts	279.0	358.0	22.6
B-B	Decline	230.1	197.3	14.3

scaled from the current 55,000 tonnes per month to 68,918 tonnes per month to cater for future requirements. As illustrated in Fig. 7 above, there is an 8347 kW shortfall in the cooling structure to achieve a return wet-bulb temperature of 29.5 °C. After evaluating the underground environment through the mass balance and the heat load study, a list of possible alternatives is proposed in Tables 2 and 3 above. Table 12 below shows possible solutions for the shortfall of airflow through the mining block to accommodate the mechanised machinery.

During the heat load study, the orange block in Fig. 7 indicated the cooling shortfall that needs to be added to the underground environment to meet the temperature design criteria. Using Table 3 as a guideline, the alternatives in Table 13 are proposed to increase the cooling.

Step 2 in Fig. 8 evaluates each of these alternatives based on the criteria used during the decision-making process. Table 4 determines the risk value if the alternative is not implemented, and the value of each alternative is shown in Table 14.

The simulation package used to develop the simulation model and predict the impact of the various alternatives is *Process Toolbox*, which is a thermohydraulic simulation software that simulates dynamic and integrated mining systems [99]. The impact of each alternative is determined using the calibrated model with an accuracy of 4.7% to the physical system. The alternatives' cost and implementation time are based on historical data of projects and quotes from suppliers. The change in ACP, cost and implementation times are listed in Table 14.

Step 3 in Fig. 9 weights the criteria using the AHP MCDM method. The paragraph below Table 7 explains

Fig. 7 Mine’s heat load graph

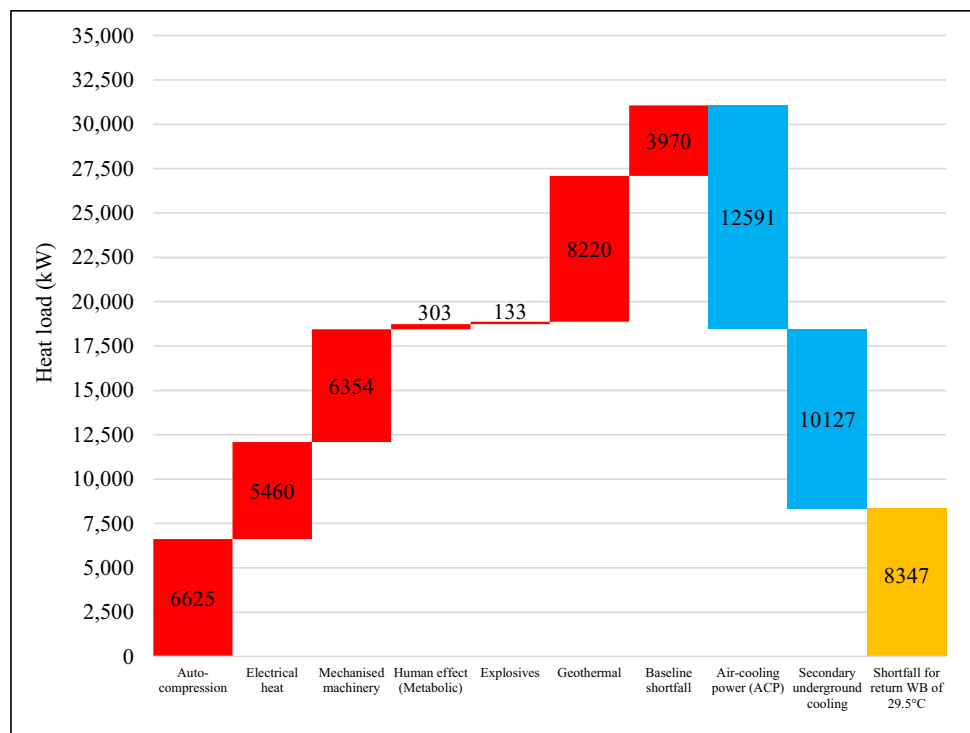


Table 12 Proposed alternatives to rectify the airflow quantity

Symbol	Alternative	Description
A ₁	Additional/new shaft	Develop a new shaft from the surface to the mining block
A ₂	Condenser 5	Develop a new condenser pond and booster fan
A ₃	Additional fans in the RAW ³	Place two fans in the east and west RAW and boost the flow to each level of the mining block
A ₄	New straight RAW to 1#	Develop a return haulage from the back of the condenser ponds to 1#
A ₅	Rehabilitate the current RAW	Re-establish the RAW between 1# and 5# to the original condition
A ₆	Additional RAW to 5#	Develop a twin RAW from 52L to 63L at 5#
A ₇	Additional intake and return haulage	Develop an additional mining block intake and return haulage

RAW = Return Airway.

Table 13 Proposed alternatives to rectify the cooling shortfall

Symbol	Alternative	Description
A ₈	Underground refrigeration	Add an underground refrigeration plant to the current system
A ₉	Decline BAC	Install a BAC in the main decline haulage
A ₁₀	1C# BAC	Install a BAC in the intake air of the 1C sub-shaft haulage
A ₁₁	Surface refrigeration	Install a surface refrigeration plant to cool some of the air going underground
A ₁₂	Electric vehicle	Change the diesel machinery to electric vehicles

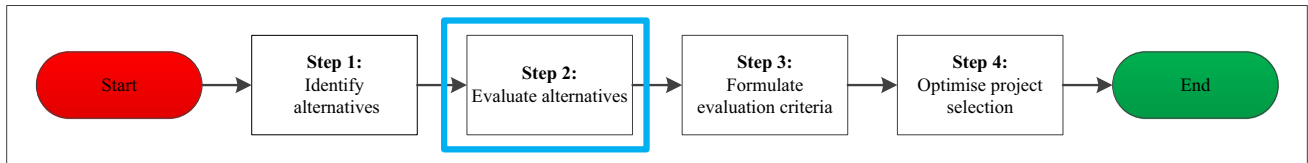


Fig. 8 Step 2 of the method - evaluate alternatives

Table 14 Mines' alternative evaluation values

Alt	Alternative	Risk	Change in ACP (W/m ²)	Cost (R M) ⁴	Imp. time (month)
A ₁	Additional/new shaft	12	366.3	363.0	36
A ₂	Condenser 5	2	223.8	9.8	8
A ₃	Additional fans in the RAW	6	510.0	39.2	18
A ₄	New straight RAW	12	102.5	219.7	27
A ₅	Rehabilitate the current RAW	9	101.2	8.0	6
A ₆	Additional RAW	12	237.4	474.7	57
A ₇	Additional intake and return haulage	12	137.7	796.9	95
A ₈	Underground refrigeration	12	528.7	15.0	3
A ₉	Intake air BAC (decline)	12	1436.7	40.1	8
A ₁₀	Intake air BAC (1C sub-shaft)	12	704.8	35.0	6
A ₁₁	Surface refrigeration	12	1569.1	42.6	6
A ₁₂	Electric vehicle	12	67.5	99.0	48

USD 1 = R17.06 (16 January 2022).

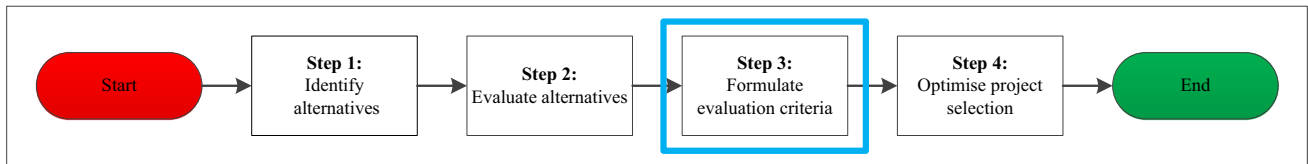


Fig. 9 Step 3 of the method - formulate evaluation criteria

the criteria's importance, contrary to the other criteria. This will assist in setting up the judgement matrix to weight the criteria in Eq. 15.

$$\begin{matrix}
 & \begin{matrix} Risk & Impact & Cost & Time \end{matrix} \\
 \begin{matrix} Risk \\ Impact \\ Cost \\ Time \end{matrix} & \begin{bmatrix} 1 & 1 & 5 & 9 \\ 1/1 & 1 & 5 & 7 \\ 1/5 & 1/5 & 1 & 3 \\ 1/9 & 1/5 & 1/5 & 1 \end{bmatrix}
 \end{matrix} \quad (15)$$

The criteria weight vector can now be calculated. Table 15 shows the relative weights of each criterion.

The judgement consistency needs to be determined to ensure the judgement matrix is acceptable and reasonable.

Using Eq. 3, the consistency element (cv_i) is calculated, which is then used to calculate the eigenvalue (λ_i). These values are shown in Table 16.

Table 15 Criteria weight

C ₁	C ₂	C ₃	C ₄
0.44	0.41	0.1	0.05

Table 16 Consistency vector and eigenvalues

i	cv_i	λ_i
1	1.79	4.1
2	1.7	4.1
3	0.41	4.0
4	0.19	4.0

The maximum eigenvalue is calculated using Eq. 5, and the values in column 3 of Table 16 to get a maximum eigenvalue of 4.05. The CI is 0.019 using Eq. 6. This gives a CR of 0.02 (2%). The CR value is below 10%, indicating that the judgement matrix is acceptable for the next step.

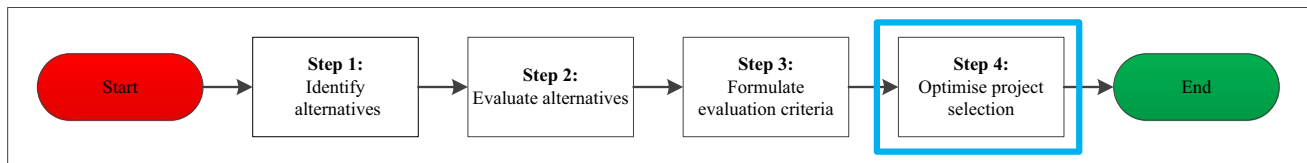


Fig. 10 Step 4 of the method - optimise project selection

Figure 10 highlights Step 4 that is used to apply the TOPSIS method to prioritise the alternatives. Using Table 14 as the decision matrix, the first aspect is calculating the weighted normalised matrix using Eq. 9. After the weighted normalised matrix is calculated, the highest and lowest attributes should be added to the V^* and V^- . Table 17 shows the range which favours the criteria.

Using the information in Table 17, the Euclidean distance to the NIS and PIS can be calculated using Eqs. 12 and 13, and are reported in Table 18.

3.3 Final Priorities

The final aspect of the method is to prioritise each alternative. The relative closeness can be calculated using Eq. 14, and the relative closeness and the priority of the alternatives are shown in Table 19.

Table 19 shows that the most suitable alternative to improve the underground environment is surface refrigeration (A_{11}), followed by the BAC in the decline (A_9) and 1C sub-shaft (A_{10}). The least suitable alternative is adding a condenser 5 (A_2).

The mine considered the priority of the alternatives in Table 19 and implemented surface refrigeration (A_{11}),

which considerably improved the underground environment during the hot summer months. Removing the first three priority alternatives from the list, the TOPSIS method was applied again, and underground refrigeration (A_8) was the second most suitable alternative to be implemented. The underground refrigeration assisted in producing constant cold-water temperatures and moving the cooling into the working areas.

3.4 Analysis

To analyse the results for the MCDM methods, the graph in Fig. 11 compares the priority with the risk value allocated to the alternatives and the impact on the underground environment.

The priority of the alternatives in Fig. 11 is indicated from left, the highest priority (A_{11}) to right, the lowest priority (A_2). Figure 11 illustrates that the alternatives with the highest risk value were preferred, as these alternatives occupied priority one to six. Priority one to five is then arranged according to their impact on the underground environment. The difference between priority five (A_1) and six (A_3), as well as priority 10 (A_5) and 11 (A_7), shows that the cost criteria influenced the priorities of these alternatives.

The decision method and Fig. 11 showed that impact of the alternatives had a large influence on the prioritisation. The project with the largest impact was prioritised first (A_{11}) and the rest of the prioritised alternatives' impact decreased.

The cost of the first four prioritised alternatives (A_{11} , A_9 , A_{10} , and A_8) are all below R50M (Table 14) whereas priority five's (A_1) cost is considerably higher (R366M). The two

Table 17 Attributes that need to be added to V^* and V^-

	Equation	Risk	Impact	Cost	Time
V^*	10	Max	Max	Min	Min
V^-	11	Min	Min	Max	Max

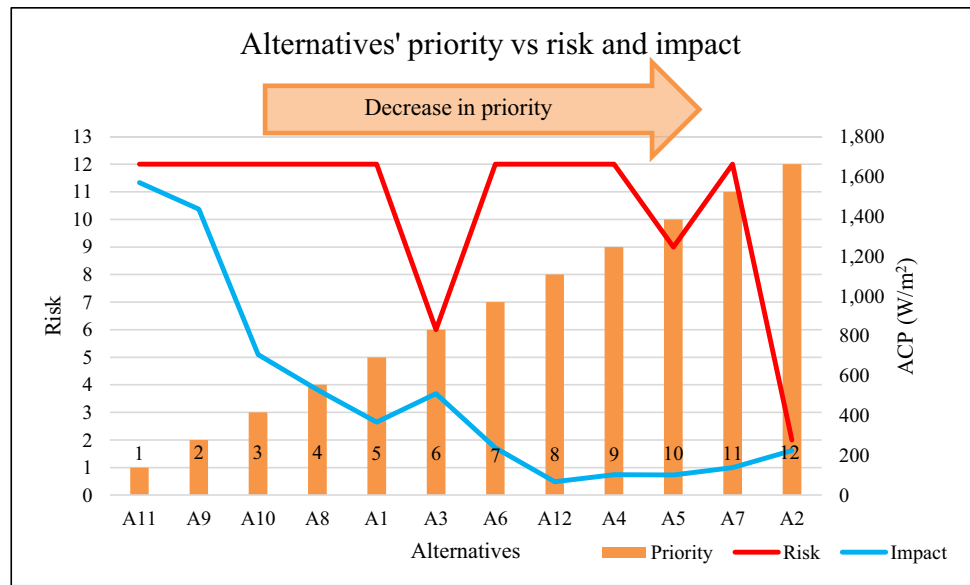
Table 18 Euclidean distance to the NIS and PIS

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}
D_i^*	0.21	0.26	0.19	0.25	0.25	0.23	0.26	0.18	0.02	0.15	0.00	0.26
D_i^-	0.14	0.09	0.12	0.13	0.12	0.13	0.12	0.16	0.27	0.18	0.29	0.14

Table 19 Relative closeness and the priority

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}
C_i^*	0.40	0.25	0.38	0.35	0.32	0.35	0.31	0.48	0.92	0.55	0.99	0.35
Priority	5	12	6	9	10	7	11	4	2	3	1	8

Fig. 11 Alternative’s comparison graph of the MCDM results



most inexpensive alternatives and most expensive alternative were prioritised last due to the other criteria’s low impact.

Figure 11 shows that TOPSIS MCDM prioritises the alternatives based on the weights of the criteria assigned in Table 15 where risk was the most important criteria followed by impact. Although the cost’ weight was smaller, the impact can be seen between priority five (A₁) and six (A₃), as well as priority 10 (A₅) and 11 (A₇).

3.5 Validation

3.5.1 Before implementation of the developed method

The case study mine was in the process of implementing projects (alternatives) before the method developed in this paper was applied. The mine started by implementing project A₂, the condenser pond 5. The projects were financially motivated, as indicated in Fig. 11 that shows A₂ is prioritised last, based on the criteria used in this method. Although alternative A₂ is the cheapest option, the risk rating and impact of the alternative on the underground environment are low. Currently, A₂ serves purely as a redundancy and is not contributing any value to the operations.

If the method developed in this paper were used to rank the alternatives earlier, the focus could have been placed on higher impact projects that realise benefits much sooner.

3.5.2 Implementing the developed method

Based on the recommendations of the developed method, the mine implemented the surface refrigeration (A₁₁) alternative prioritised first in Table 19. This section will elaborate on

the method’s accuracy in predicting the results and prioritising the alternatives.

The difference between the simulated impact ACP and the actual varies by 50.5 W/m². On the day of the ventilation audit, the distribution of the ACP through the mine was different from predicted since some operational challenges changed the airflow distribution. Even with these operational challenges, the change in ACP between the simulated and actual differed by only 6% [72, 100]. This is in an acceptable margin to verify that the simulation model gives accurate results.

The cost quote of the surface refrigeration was R 46,605,000 during the evaluation stage of the project, but the cost of the project came to be R 51,594,000. The proposed implementation time for the project was 6 months, but from the start until the commissioning of the Surface Refrigeration project took 2 months longer than predicted. Table 20 summarises the predicted and actual values of the Surface Refrigeration project.

The values summarised in Table 20 were used in Table 14, alternatives’ evaluation values, with the other values and Step 3 and Step 4 were redone to ascertain the impact these changes will have on the prioritising the alternatives.

Table 20 Surface Refrigeration predicted compared to actual values

Criteria	Model predicted values	Actual values
Risk	12	12
Impact (W/m ²)	1569.1	1671.8
Cost (R M)	46.6	51.5
Implementation time (months)	6	8

The prioritising order of the alternatives remained the same, with the surface refrigeration model still ranked first. This section shows that the method developed can accurately predict the results and prioritisation of the alternatives.

If the method developed in this paper were used to rank the alternatives earlier, the focus could have been placed on higher impact projects that realise benefits much sooner.

In validating the method, the two sections show that the method assists the mine in selecting the most suitable alternative and, with the developed method, the correct decision can be made. The section also shows that the method's results are accurate and can be used to select the most suitable alternative during the decision-making process.

4 Conclusion

The study's objective to develop a method to identify and prioritise large Capex environmental improvement projects was achieved. Based on the case study, the developed method is a valuable tool for identifying environmental improvement alternatives, as shown through the implementation of the prioritised projects. Using simulations to calculate the impact, improves the accuracy of the decision-making process. By prioritising the alternatives using MCDM, the decision-maker has a clear understanding of the critical time spend on improving the underground conditions.

Recommendations for further studies include expanding this method into a tool for decision-makers in the ventilation field during smaller project's identification and prioritising process. As the MCDM method is developed to include the decision-makers' experience during the criteria weighting, this should be the focus to decrease the possibility of bias.

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Data Availability The authors declare that the data supporting the findings of this study are available within the article.

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