

Applying multi-criteria decision-making processes to deep-level mine ventilation projects

J Swanepoel

 **orcid.org/0000-0002-0216-5680**

Thesis accepted in fulfilment of the requirements for the degree
Doctor of Philosophy in Engineering with Mechanical
Engineering at the North-West University

Promoter: Dr JH van Laar
Co-promotor Dr JC Vosloo

Graduation: August 2023
Student number: 31551939

ACKNOWLEDGEMENTS

As the author of this thesis, I would like to express my gratitude by thanking the following persons that influenced the completion of this research study:

- Prof Eddie Mathews and George Mathews for this unique opportunity to do my post-graduate studies while developing my engineering skills in the industry. *Enermanage (Pty) Ltd* for the financial support to finish my studies.
- To my study leader, Dr Jean van Laar, and my mentors, Dr Jan Vosloo and Dr Diaan Nell, for guiding me to deliver the best work possible.
- My parents, Johan and Caron Swanepoel, for their love and support. I am privileged to have parents that sacrifice so much for me.
- A special thanks to Juanita Swanepoel, my wife. Thank you for believing in me and supporting me through the whole process. Thank you for understanding when I had to work late and the time spent with you was little. I love you very much.
- My Heavenly Father, thank You for the ability to complete my studies, and this was only possible with Your guidance. Thank You for all Your unconditional love.

ABSTRACT

Title: Applying multi-criteria decision-making processes to deep-level mine ventilation projects

Author: J. Swanepoel

Promoter: Dr J. van Laar

Keywords: Multi-criteria decision-making method (MCDM), Deep-level underground mining, Ventilation, Analytic Hierarchy Process (AHP), Environmental improvement, Project ranking, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Highlights

- Ventilation and cooling project selection for deep-level underground mines.
- Development of a method to evaluate and rank environmental improvement projects.
- Ventilation simulations to determine underground environmental impact.
- Using AHP and TOPSIS multi-criteria decision-making methods to prioritise ventilation projects.

Deep-level underground mining costs in South Africa are continuously rising due to the increased depth at which gold is being mined, increasing the need for improved cooling requirements. Therefore, mines must evaluate the various ventilation and cooling optimisation projects required to be implemented throughout their “life of mine” (LOM).

The ventilation system of a deep-level underground mine is complex and challenging to evaluate holistically. This study’s solution presents ventilation simulations to determine the impact of the projects on the underground environment. The evaluation of an environmental improvement project to decrease the safety risk, while improving underground conditions and best suit the current economic climate, is an essential aspect of the solution developed in this study.

This study develops a method to evaluate and rank underground environmental improvement projects to improve thermal comfort in underground mines. The solution utilises 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 five criteria: project risk (risk mitigation), the impact on the underground mine environment (such as thermal comfort), cost, energy efficiency, and implementation time.

The method was implemented on a mechanised deep-level underground mine where the ventilation system was not adapted over time to consider the mine's dynamical development. The method showed that surface refrigeration is the most suitable project solution, and it was implemented at the case study mine to validate 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.

This study led to a publication titled "*Prioritisation of environmental improvement projects in deep-level mine ventilation system*" in the journal *Mining, Metallurgy & Exploration*.

JOURNAL ARTICLE

An article based on the work in this thesis was published in the international peer-reviewed journal, Mining, Metallurgy & Exploration. The published article is titled “*Prioritisation of environmental improvement projects in deep-level mine ventilation systems*”. The full article can be found in Appendix G.

Mining, Metallurgy & Exploration
<https://doi.org/10.1007/s42461-023-00738-w>



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

J. Swanepoel¹ · J. C. Vosloo¹ · J. H. van Laar¹  · W. A. Pelsers²

Received: 5 October 2022 / Accepted: 1 February 2023
© The Author(s) 2023

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

 J. Swanepoel
jswanepoel@remms2.com

¹ Center for Research and Continued Engineering Development (CRCED) Pretoria, North-West University, Pretoria, South Africa

² Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa

Published online: 27 February 2023

 Springer

Citation:

J. Swanepoel, J. Vosloo, J. van Laar, and W. Pelsers, “Prioritisation of environmental improvement projects in deep-level mine ventilation systems,” *Min Metall Explor*, vol. 1, pp. 1–18, Feb. 2023, doi: 10.1007/S42461-023-00738-W

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	II
ABSTRACT	III
JOURNAL ARTICLE	V
LIST OF FIGURES	VIII
LIST OF TABLES.....	X
LIST OF EQUATIONS.....	XII
NOMENCLATURE	XIII
GLOSSARY.....	XVI
1. INTRODUCTION TO MINING PROJECT SELECTION.....	1
1.1 Preamble.....	1
1.2 Sustainable underground deep-level mining	1
1.3 Multi-Criteria Decision-Making methods.....	11
1.4 The benefits of MCDM versus currently used methods.....	13
1.5 Mine climate simulations.....	14
1.6 Literature analysis	14
1.7 Problem statement	20
1.8 Study objectives	20
1.9 Novel contributions	20
1.10 Study outline.....	26
1.11 Conclusion.....	27
2. DEVELOPMENT OF A NEW RANKING METHOD	28
2.1 Preamble	28
2.2 Step 1: Establish evaluation environment	28
2.3 Step 2: Evaluate projects.....	39
2.4 Step 3: Formulate evaluation criteria	46
2.5 Step 4: Optimise project selection	51
2.6 Verification of method.....	55
2.7 Conclusion.....	56

3. APPLICATIONS AND RESULTS	57
3.1 Preamble.....	57
3.2 Case study mine.....	57
3.3 Result analysis	85
3.4 Validation.....	87
3.5 Conclusion.....	92
4. CONCLUSION AND RECOMMENDATIONS	94
4.1 Study summary.....	94
4.2 Novel contributions	95
4.3 Conclusion.....	95
4.4 Recommendations for future work	96
BIBLIOGRAPHY	97
APPENDIX A: RETURN TEMPERATURES	110
APPENDIX B: DETERMINE MODEL ACCURACY	111
APPENDIX C: PROJECT DETAIL	112
APPENDIX D: QUANTIFY IMPACT DETAIL.....	115
APPENDIX E: DETAILED COST ANALYSIS	125
APPENDIX F: PROJECT POWER USAGE	128
APPENDIX G: PUBLISHED ARTICLE	129

LIST OF FIGURES

Figure 1-1: Sustaining and Development & Expansion Capex [2]	2
Figure 1-2: Minerals years left to depletion [3].....	2
Figure 1-3: Top 10 gold-producing countries [5]	3
Figure 1-4: South Africa's gold production from 2010-2019 (Adapted from [7] and [8]).....	4
Figure 1-5: VRT increase with mine depth increase [14]	5
Figure 1-6: Refrigeration required underground as the depth of mining increases [13].....	6
Figure 1-7: Proposed method outline to indicate novel contributions.....	21
Figure 1-8: Research methodology alignment with thesis layout (Adapted from [104]).....	26
Figure 2-1: Project evaluation and ranking method	28
Figure 2-2: Five phases of Step 1 of this method	29
Figure 2-3: Schematic of the typical boundary selection	30
Figure 2-4: Representation of the 3D GUI of a ventilation network.....	34
Figure 2-5: PTB thermohydraulic components	34
Figure 2-6: PTB's additional capabilities	35
Figure 2-7: Steps to build and calibrate a ventilation simulation (Adapted from [103]).....	35
Figure 2-8: Calibration parameters: Air tunnel input interface changes	36
Figure 2-9: Five evaluation criteria of Step 2 of the method	41
Figure 2-10: Output interface of an AirTunnel component.....	44
Figure 2-11: Output interface of an AirNode component	44
Figure 2-12: Two phases of Step 3 of the method.....	46
Figure 2-13: Schematic framework of the AHP method.....	46
Figure 2-14: Visual presentation of the TOPSIS method.....	52
Figure 2-15: Three phases of Step 4 of the method	53
Figure 2-16: Complete method to evaluate and rank projects	56
Figure 3-1: Top view of the mining complex.....	57
Figure 3-2: Step 1 of the methodology – Establish evaluation environment.....	58

Figure 3-3: The mine’s boundary	59
Figure 3-4: DXF of Level 291	60
Figure 3-5: Airflow plan for Level 291	61
Figure 3-6: Mine’s refrigeration circuit layout.....	62
Figure 3-7: Cooling infrastructure information - Daily reporting.....	63
Figure 3-8: Schematic of the intakes and returns of the mine.....	63
Figure 3-9: DXF model of the mine in PTB.....	66
Figure 3-10: Ventilation network of tunnels and nodes in PTB for Level 291	66
Figure 3-11: Cooling infrastructure, refrigeration plants in PTB	67
Figure 3-12: Percentage error on the model calibration	67
Figure 3-13: Step 2 of the methodology – Evaluate projects	70
Figure 3-14: Mine’s highest risks - Visual indication	71
Figure 3-15: Step 3 of the methodology – Formulate evaluation criteria.....	77
Figure 3-16: The mine’s judgement matrix	78
Figure 3-17: The consistency vector	79
Figure 3-18: Step 4 of the methodology – Optimise project selection	80
Figure 3-19: Aerial view of the planned location for the surface refrigeration project	84
Figure 3-20: Surface refrigeration installed at the case study mine	84
Figure 3-21: Projects comparison graph of the MCDM results	85
Figure 3-22: Projects ranking against the cost and impact	86
Figure 3-23: Condenser chamber with shotcrete.....	88
Figure 3-24: Condenser pond 5 pumping station	89
Figure 3-25: Condenser pond 5 booster fan.....	89
Figure G-1: Confirmation of the published article	129

LIST OF TABLES

Table 1-1: Temperature legal limit [19].....	5
Table 1-2: Summary of different studies on evaluating and selecting projects.....	8
Table 1-3: MCDM methods with description.....	12
Table 1-4: The results, relating to methods used, from the literature review [63].....	13
Table 1-5: Summary of the research literature review	15
Table 1-6: Novel contributions summary	25
Table 2-1: Information required and departments.....	32
Table 2-2: Possible issues and examples of ventilation projects	38
Table 2-3: Possible issues and examples of cooling projects	39
Table 2-4: Example of the risk matrix (Developed with [129]).....	42
Table 2-5: Meaning of probability rows in risk matrix (Developed with [129]).....	42
Table 2-6: Meaning of consequence column in risk matrix (Developed with [129]).....	43
Table 2-7: Evaluation criteria	47
Table 2-8: Measurement's scale of pairwise comparison [136]	48
Table 2-9: Verification of the proposed method.....	55
Table 3-1: The mine's intake flows and temperatures	64
Table 3-2: The mine's cooling infrastructure.....	65
Table 3-3: Proposed projects to rectify the airflow quantity	68
Table 3-4: Proposed projects to rectify the cooling shortfall	69
Table 3-5: Risk analysis for each project.....	72
Table 3-6: Project environmental impact.....	73
Table 3-7: Capital cost for the projects.....	74
Table 3-8: Difference in power usage of the projects.	75
Table 3-9: Implementation time of the proposed projects	76
Table 3-10: Projects' evaluation values	76
Table 3-11: Values allocated during the criteria weighting.....	78

Table 3-12: Criteria weight	78
Table 3-13: Eigenvalues	79
Table 3-14: Normalised decision matrix (R_{ij})	81
Table 3-15: Weighted normalised decision matrix (V_{ij})	81
Table 3-16: PIS for the criteria (V^*)	82
Table 3-17: NIS for the criteria (V^-)	82
Table 3-18: Project's distance to the PIS and NIS	82
Table 3-19: Relative closeness (C_i^*) and rank	83
Table 3-20: Projects ranked in order of preference	83
Table 3-21: Possible projects to improve the mine	88
Table 3-22: RAW total mass flow before and after CP5 implementation	89
Table 3-23: The surface refrigeration project's audit data	90
Table 3-24: Surface refrigeration actual results comparison	91
Table 3-25: Surface Refrigeration predicted compared to actual values	92
Table A-1: Mine's return flows and temperature	110
Table B-1: Model's percentage error values	111
Table C-1: Detail ventilation projects description	112
Table C-2: Detail cooling projects descriptions	113
Table D-1: Changes to the baseline simulation model per project - Ventilation	115
Table D-2: Changes to the baseline simulation model per project - Cooling	120
Table D-3: Change in ACP for a level of the different projects (A_1 - A_5)	123
Table D-4: Change in ACP for a level of the different projects (A_6 - A_9)	123
Table D-5: Change in ACP for a level of the different projects (A_{10} - A_{13})	124
Table E-1: Constant development cost used during cost analysis	125
Table E-2: Cost analysis - detail	125
Table F-1: Project power usage	128

LIST OF EQUATIONS

Equation 2-1: Calculating air cooling power [113].....	31
Equation 2-2: Calculate the simulation percentage error	37
Equation 2-3: Judgement matrix [52].....	48
Equation 2-4: Normalised the judgement matrix [74].....	49
Equation 2-5: Calculate the relative weights.....	49
Equation 2-6: Mathematical condition [137].....	49
Equation 2-7: Calculate consistency vector, CV	50
Equation 2-8: Calculate eigenvalue [139].....	50
Equation 2-9: Calculate the highest eigenvalue [96].....	50
Equation 2-10: Consistency index (CI) [140]	50
Equation 2-11: Consistency ratio (CR) [140]	50
Equation 2-12: Decision matrix [96]	51
Equation 2-13: Weighted normalised matrix [74].....	53
Equation 2-14: Positive ideal solution [87].....	53
Equation 2-15: Negative ideal solution [87]	54
Equation 2-16: Project's distance from PIS [65]	54
Equation 2-17: Project's distance from NIS [65]	54
Equation 2-18: Relative closeness [74]	54

NOMENCLATURE

Abbreviations

Abbreviation	Description
ACP	Air cooling power
AHP	Analytic hierarchy process
BAC	Bulk air cooler
BCG	Boston Consulting Group
CC	Cooling circuit
CI	Consistency index
CR	Consistency ratio
DPM	Diesel particulate matter
DMRE	Department of Mineral Resources and Energy
DXF	Drawing exchange format
FOG	Fall of ground
GUI	Graphical user interface
IRR	Interest rate of return
KPIs	Key performance indicators
LOM	Life-of-mine
MB	Mining block
MCDM	Multi-criteria decision-making
MHSA	Mine Health and Safety Act (MHSA), 1996 (Act No 29 of 1996)
NIOSH	National Institute for Occupational Safety and Health
NIS	Negative ideal solution
NPV	Net present value
PIS	Positive ideal solution
PMG	Platinum group metals
PTB	Process Toolbox

RAW	Return airway
RI	Random index
SCADA	Supervisory Control and Data Acquisition
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VRT	Virgin rock temperature
VOD	Ventilation-on-demand

List of symbols

Symbol	Description	Units
k	Air Cooling Power	W/m ²
D_i^*	Alternative distance from PIS	-
D_i^-	Alternative distance from NIS	-
I_0	Capital cost	R
cv_i	Consistency element	-
CV	Consistency vector	-
w	Criteria weight	-
C_x	Criteria	-
λ_i	Eigenvalue	-
V^-	Euclidean negative ideal solution	-
V^*	Euclidean positive ideal solution	-
IRR	Interest Rate of Return	%
[A]	Judgement matrix	-
y_m	Measured value	-
$\bar{a}_{ij}$	Normalised element	-
t	Number of time periods	Years
F_k	Operational cost	R
%E	Percentage error	%
C_i^*	Relative closeness	-
#	Shaft	-
y_s	Simulated result	-
n	Square matrix of the order	-
T_w	Wet-bulb temperature	°C
v	Velocity	m/s

GLOSSARY

“Alternative”	Multi-criteria decision-making methods’ naming convention for the options to select from during the process.
“Dry-bulb temperature”	Ambient temperature measured by a thermostat without being affected by the air’s moisture contents.
“Deep-level mine”	Underground mines that extend underground more than 1.5 km.
“Fall of ground”	The support of an underground opening disintegrates, and the roof caves in, leaving rocks on the ground.
“Fridge plants”	Underground refrigeration plants that use gas as a heat transfer agent to produce chilled water.
“Haulage”	An underground tunnel surrounded by solid rock.
“Mine layouts”	Layout that contains the mined-out areas with the air temperature and air flows.
“Mining block”	The area where the mining operations take place.
“Mining operations”	All the critical operations in a mine that are needed to operate a mine efficiently, and it includes ventilation, mining, and engineering.
“Mechanised mining”	A mining design using machinery to mine that does not use rail-based tracks.
“Level”	Mined out areas that are the same underground distance from the surface.
“Return air”	Hot and contaminated air that needs to return to the surface.
“Shaft”	The connection of each level to the surface. It can be equipped with a cage or used for air.
“Underground”	Below the surface that is mined out to accommodate humans, structures, and equipment.
“Wet-bulb temperature”	Temperature includes the air’s moisture contents and is measured by a thermostat with a wet cloth.

1. INTRODUCTION TO MINING PROJECT SELECTION

1.1 Preamble

The background of the mining industry and deep-level underground mining in South Africa is discussed in the first section. The current standing, as well as the future of deep-level underground mining, will be discussed. Various decision-making methods used in the mining industry will be investigated.

The problem statement and study objectives will be developed from available literature on decision-making in the mining industry. Concurrently, the novel contributions will be elaborated on at the end of this chapter.

1.2 Sustainable underground deep-level mining

South Africa is a mineral-rich country with many industrial processes dependent on the minerals unearthed here. Despite this, the mining industry has declined during the last two decades. An annual survey of mining companies by the Fraser Institute ranked South Africa 75th out of 84 countries for investment attractiveness [1]. The survey showed that large international companies are hesitant to invest in South Africa's gold mining industry because of a long list of factors.

Boston Consulting Group (BCG) wrote a report entitled *Working together to reenergize the South African mining industry*, to establish interventions required to attract new investments to the mining industry. In the report, BCG highlighted that there is a decrease in new investment opportunities in the mining industry, which is substantiated when comparing the "Sustaining Capex" and "Development & Expansion Capex" of South Africa against a group of top mining countries [2]. Figure 1-1 shows the Sustaining and Development & Expansion Capex comparison between South Africa and the top mining countries.

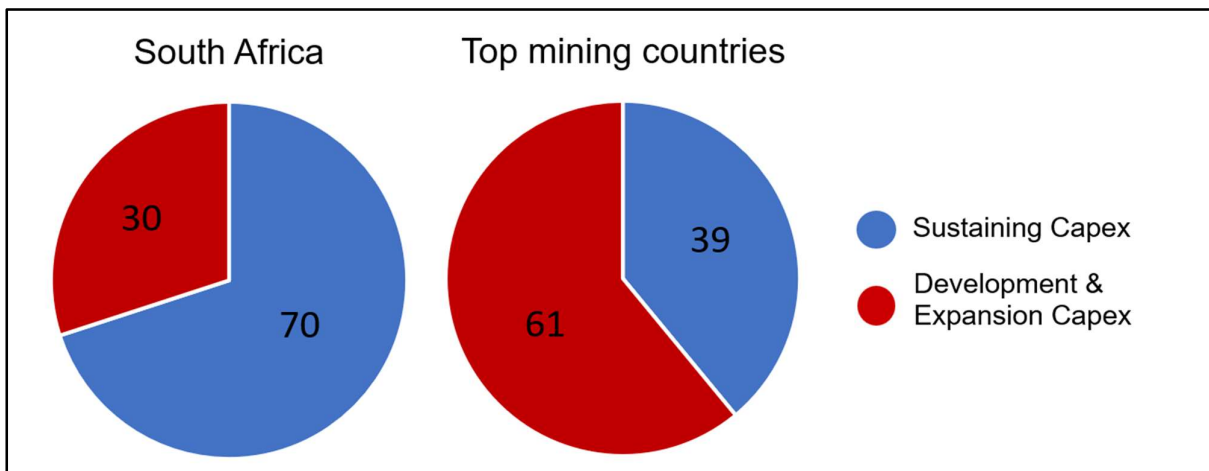


Figure 1-1: Sustaining and Development & Expansion Capex [2]

The Sustaining Capex in Figure 1-1 refers to the capital expenditure to sustain and maintain current operations. The Development & Expansion Capex refer to the capital expenditure required to develop new products and expand existing operations. Figure 1-1 shows that most of South Africa's expenditure is utilised to maintain the current operations while other countries invest more into new development and expansion projects.

Statistics South Africa (Stats SA) publishes in their *Environmental economic accounts compendium*, the years to resource depletion of the gold, coal and platinum group metals (PMGs) reserves every five years [3]. Figure 1-2 illustrates the latest number of years to resource depletion by mineral.

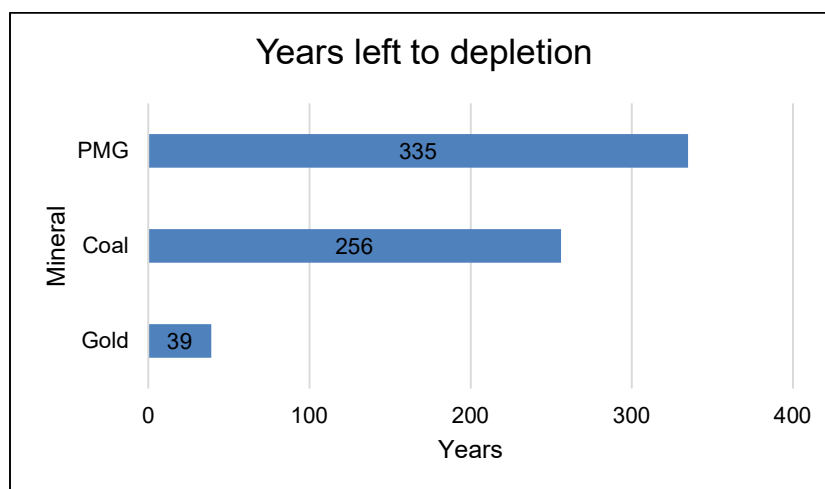


Figure 1-2: Minerals years left to depletion [3]

Figure 1-2 shows that the remaining years of gold reserves in South Africa are far less than the other two mineral groups.

South Africa was once one of the top gold producers globally, with a peak of 1 000 tonnes of gold in 1970 [4]. Since then, gold production has decreased to such an extent that South Africa struggles to stay among the Top 10 gold-producing countries. Figure 1-3 shows the Top 10 gold-producing countries with tonnes produced in 2021 [5].

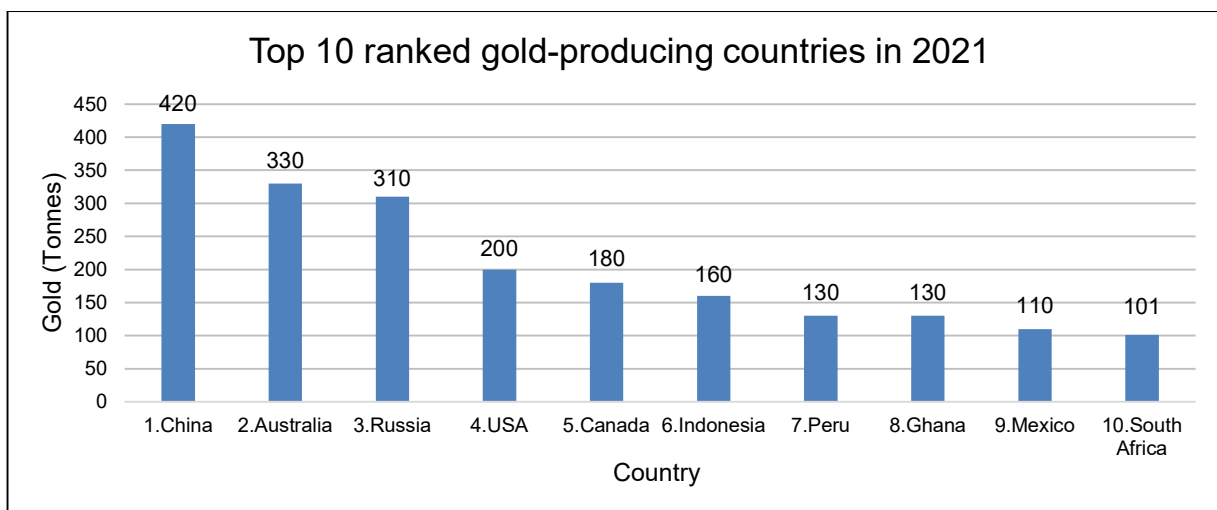


Figure 1-3: Top 10 gold-producing countries [5]

The main reasons South Africa's gold production has been declining over the past 11 years are attributed to decreasing gold reserves and a drastic increase in the cost to mine gold. This increase in mining cost can be attributed to rising electricity prices, mining depth, operations' age, and increased labour costs [6]. Figure 1-4 shows the cost of mining gold and the amount produced over the last ten years (2010-2019).

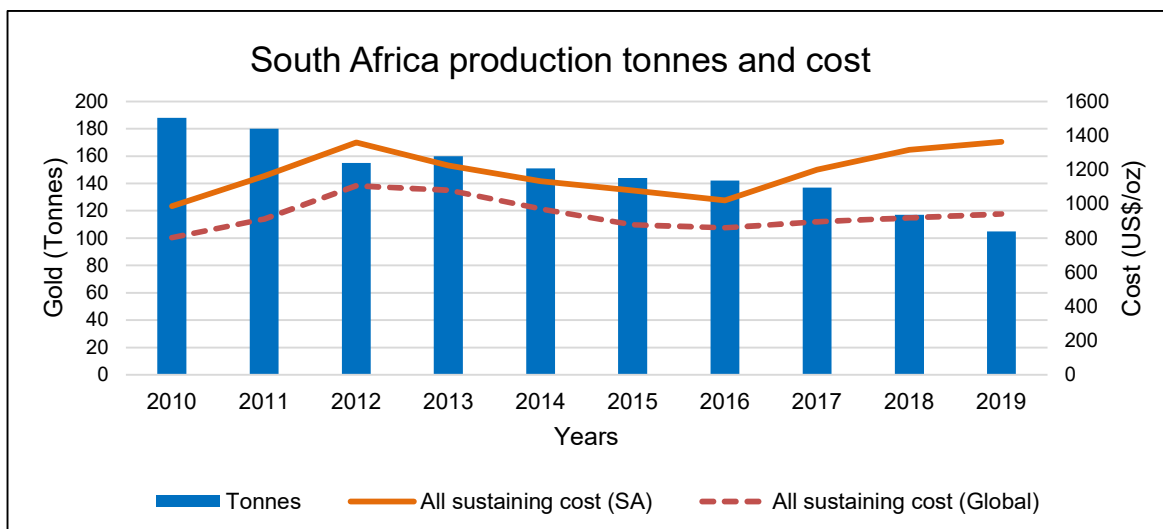


Figure 1-4: South Africa's gold production from 2010-2019 (Adapted from [7] and [8])

Figure 1-4 shows that the cost to extract gold in South Africa increased while the amount of gold produced decreased. The world's gold producers' all-sustaining average cost is 941 US\$/oz, while at the same stage South Africa's all-sustaining average cost is 1 364 US\$/oz [8]. A large part of the increase in all-sustaining costs is due to the annual energy tariff increase of 753% from 2008 to 2021 [9]. The most considerable amount of the total energy demand in the mining sector is supplied through electricity, with coal, petroleum products and gas only making up 30% [10]. The negative impact of rising costs in the gold mining industry is proven by the large gold producers, e.g., AngloGold Ashanti and Goldfields selling their gold mining assets [11].

The drastic cost increase in the mining industry calls for strategic capital spending for the industry to survive.

1.2.1 Deep-level underground environment

Six out of the top ten deepest mines in the world are situated in South Africa, with the deepest one at a depth of 3.9 km being AngloGold Ashanti's Mponeng gold mine [12]. With the depth of mines increasing, a safe underground working environment becomes an increasing challenge. Heat increases as the depth of the mine increase, and the two main drivers behind this are the virgin rock temperature (VRT) and auto-compression.

The average VRT at the Mponeng mine can be as high as 66°C [13]. Figure 1-5 shows that the VRT increases as the depth of mining increases for the two major mining districts in South Africa.

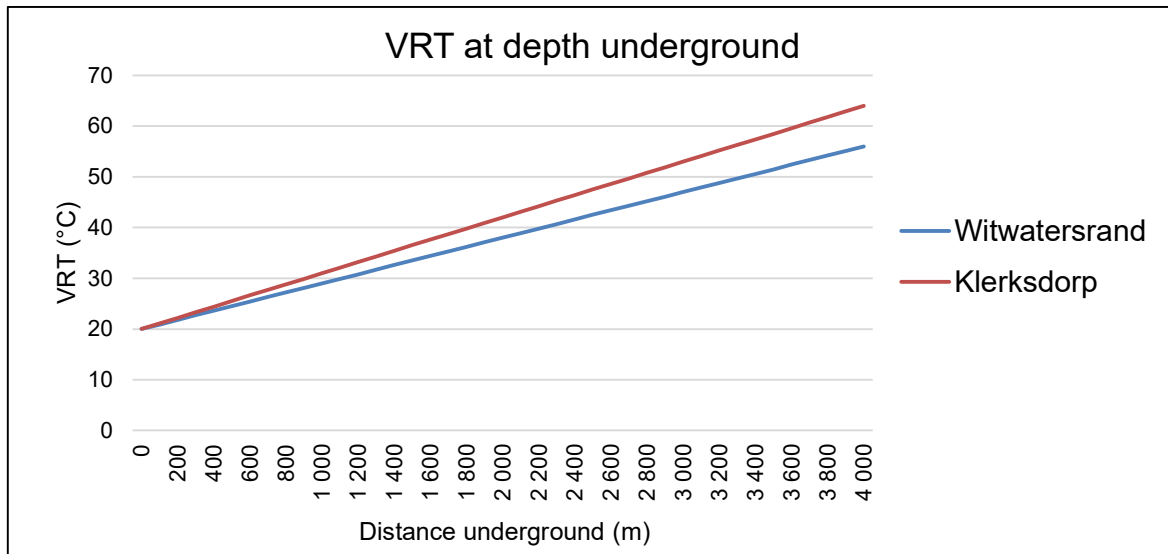


Figure 1-5: VRT increase with mine depth increase [14]

The VRT increase, as shown in Figure 1-5, means a more significant difference between the rock and air temperatures, which will cause the heat to flow from the rock to the air [15], [16].

Auto-compression is the air density increase as the air descends vertically down the mine. The temperature of the air can increase by up to 10°C per kilometre of air that descends [15], [17]. Auto-compression lowers the air's cooling ability to counteract the increased VRT sufficiently and to provide satisfactory underground conditions without implementing artificial cooling [15], [18].

Since the surrounding environment heat up as mining deepens through auto-compression and VRT, the Department of Mineral Resources and Energy (DMRE) prescribes the maximum legal temperatures at which a human should perform work. Table 1-1 presents these legal wet- and dry-bulb maximum temperature requirements.

Table 1-1: Temperature legal limit [19]

Parameter	Limit
Maximum Wet-bulb temperature (°C)	32.5
Maximum Dry-bulb temperature (°C)	37.0

Above these limits, limited heat exchanges can occur between the human body and the environment, which can pose a danger since the specific cooling power of the air is lower than what the human body exerts [20]. Should the temperature increase above the legal limit, the workforce would have to withdraw from the workplace, impacting the productivity of a mine. Ventilation and refrigeration systems are thus implemented to maintain legal underground climatic conditions.

1.2.2 Mine cooling systems

(i) Refrigeration

Refrigeration and ventilation systems account for 40-50% of a mine's energy consumption and are mainly used to counter these increased temperatures [21], [22]. As a result, ventilation and refrigeration are mainly impacted by the rise in electricity prices, and careful consideration should be given to the respective cooling strategies implemented.

The mines' cooling strategy should also be variable because as the depth of the mine increases, cooling methods changes. Mackay *et al.* [23] developed a cooling hierarchy to indicate what type of refrigeration should be introduced when the depth of the mine exceeds a certain threshold. Figure 1-6 shows the refrigeration system required to overcome increased temperatures.

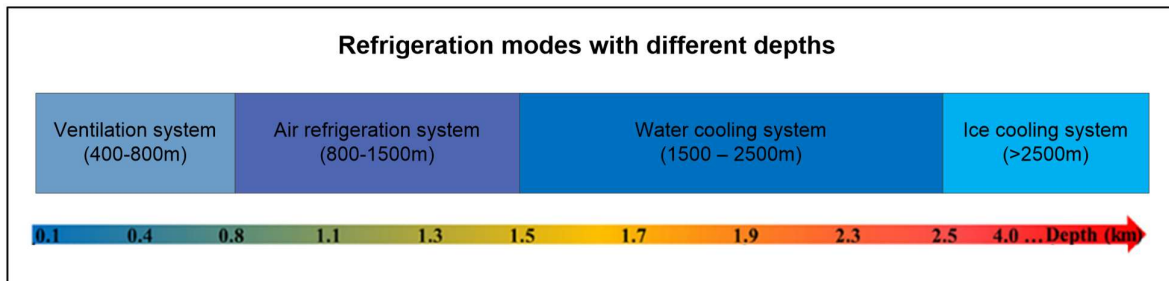


Figure 1-6: Refrigeration required underground as the depth of mining increases [13]

As seen in Figure 1-6, up until 800 m, underground ventilation is adequate to cool the mine. An air refrigeration system is required when the depth increases between 800 m and 1 500 m. As the mine depth increases between 1 500 m and 2 500 m, a refrigeration system is required to cool water and supply underground infrastructure for positional cooling. Where depth increases to below 2 500 m, an ice-cooling system is required to cool the working areas.

(ii) Ventilation planning

The infrastructure for cooling a mine is expensive and should be part of the mine design phase. As the mine deepens and the production increases, cooling infrastructure changes should be planned and introduced.

Ventilation planning is an integrated and essential process during mine planning. During the formal feasibility phase, all the primary ventilation and infrastructure for the life-of-mine (LOM) should be considered [24]. Throughout this phase, it is the most effective to make changes to the system and develop the phase-in cooling strategy as the LOM develops, as stated in Figure 1-6. Different simulation software has been developed during the last decade to assist the occupational hygienist in more accurate and dynamic planning [25], [26].

(iii) Simulations

Simulation software is one of the tools used by occupational hygienists and planners to accurately calculate if sufficient cooling and ventilation, to meet the requirements for the LOM, are available [25], [26]. In addition, the software can conduct predictive modelling to determine if a solution will satisfy the desired design [27]. Predictive modelling enables testing of “what-if” scenarios without implementing the scenarios in the physical system. Some simulation software can incorporate different systems to simulate the unpredictable nature of the underground environment [28], [29]. This supports the mine at the planning stage with more accurate decision-making input for the mine’s cooling and ventilation in future.

As exploration develops and more gold is discovered, mines extend their initial planned production forecasts, and the LOM is updated. A “flexible” ventilation and cooling plan can absorb these changes and develop during planning [24]. However, not all mines keep the ventilation and cooling plan updated due to increased mining costs that can lead to cost-cutting and deteriorating infrastructure [8].

Simulation software makes it critical to ensure that the ventilation and cooling systems are adapted, or projects initiated to improve the underground environment so that the conditions meet the respective requirements stated in Table 1-1.

1.2.3 Selecting environmental improvement projects

In the last decade, many studies have been done on improving the ventilation and cooling system while choosing which project would be the most suitable for the respective operational mine.

Table 1-2 will expand various previous studies on evaluating and selecting the most suitable ventilation and cooling projects. The underground environment stated in this study focuses on the thermal conditions and not the occupational parameters such as dust, noise, radiation, and methane.

The studies that appear in Table 1-2 evaluate ventilation and cooling projects. The second column in Table 1-2 gives an overview of the study. The third column highlights whether an explicit selection method was used during the project evaluations, while the fourth column highlights the shortcoming based on how the best projects were selected.

Table 1-2: Summary of different studies on evaluating and selecting projects

Main Author	Overview	Selection method	Shortcomings	Ref. nr.
Acuña	The effectiveness and efficiency of three auxiliary ventilation strategies were compared by simulating the ability to keep contaminant concentrations below the required limit. The base case of a continuous-running ventilation system was the control, while two additional strategies were compared.	No formal decision method.	The contaminants were the only variable used to evaluate the effectiveness and efficiency linked to cost saving. The risk and thermal conditions underground were not part of this study.	[30]
Baiden	Baiden <i>et al.</i> used a simulation model to optimise the benefits and justify control of Ventilation-on-demand (VOD). In conclusion, the author noted that this is an initial step to show how simulations are used during the decision process.	The decision process is based on controlling the ventilation system's cost. Cost analysis.	The main motive of the study was only to highlight the energy demands between the traditional and the VOD system.	[31]
Bascompta	The impact of the heat contribution to the underground environment for diesel and electrical machinery was analysed in this study. Simulation software and theoretical equations were used during this assessment.	The difference between the two options was evaluated, but no decision was taken.	The decision was not made because the author feels more aspects should be considered, like the flexibility of the fleet because of a trolley or cable and suitable batteries, before making the decision.	[32]
Cheng	A computer-based mine ventilation consultation software model was presented. The program uses mathematical models to evaluate and select the best ventilation system.	The Monti-Carlo analysis is used to select the best system.	The analytic hierarchy process (AHP) is only used to allocate a reliability value. Caution was raised that the index system would not completely model the ventilation system.	[33]
De Souza	The mathematical models and techniques used in ventilation computer modelling were discussed in this paper. A case study was presented to show the steps in using simulation modelling and model different scenarios to optimise a mine ventilation system.	The most optimal ventilation system criteria were based on practicality and economic benefit. Cost-benefit analysis.	No detail on the different scenarios and how they were selected was presented.	[34]

Du Plessis	Strategies are discussed to reduce the energy usage of cooling and ventilation systems. A simulation network model was incorporated to see how it can assist with the current and future conditions. The possible optimisation scenarios could then be simulated to choose the most energy-efficient system with proper workplace conditions.	The decision process' main goal was to obtain the most energy-efficient (energy savings) system, and this was only done using a cost-benefit analysis.	Cost savings was the primary strategy surrounding the optimisation of the system. Did not compare different strategies.	[35]
Du Plessis	The ventilation and cooling of Beatrix mine require optimisation by reducing the operational cost through a simulation model. The best fan configuration was ranked based on the power saving multiplied by the amount of air reduced, while the cooling project was selected based on the annual saving in pumping cost.	The final decision was based on the decision-maker's experience and judgement – no formal decision method was followed.	The optimal system was an energy-efficient one that satisfied the design workplace conditions. Risk and benefits were included through deliberations as it is not monetary values. Safety was only considered based on the reduction of airflow.	[36]
Krog	The National Institute for Occupational Safety and Health (NIOSH) used simulation models to identify and develop three stopping methods to improve ventilation. This paper describes how these methods should be implemented at an operational mine during the different development phases.	No formal decision method.	The ventilation methods were not compared, and no decision was made on which ventilation system was the best.	[37]
Mackay	This article discussed the possible technologies; and costs associated with technologies; that could be used in the future of a deep-level mine. A simulation was used to determine the break-even depth when the different refrigeration should be phased in for the specific mine. This serves as a review study of refrigeration technology.	There was no formal decision method, as no decision was made about the best project.	The planning document links up with Figure 1-6. These were proposed projects for future milestones the mine plan to reach. Although different projects were evaluated, projects were never compared, or decisions were made about which projects were found to be the best.	[23]
Maré	The authors used simulations to improve the energy savings of the cooling system by introducing advanced strategies.	Only a cost-benefit analysis was done to determine the feasibility of the energy-saving measures.	The study was based on energy management and was the main deciding factor of the project.	[38]
Mathews	Mathews developed a planning method that uses dynamic simulation model software to solve complex and integrated cooling systems.	Only a cost-benefit analysis was done.	A cost-benefit analysis was done to determine the impact of the project.	[28]

Nel	Nel et al. developed a method to assist mine personnel in evaluating operational changes based on set key performance indicators (KPIs) and operational costs.	No formal decision method.	The decision-maker's discretion was used to select the best solution to improve operational efficiency (energy savings). This was done at the end by not selecting the best-ranked option but changing the option based on a non-numerical risk assessment. The method opens the decision-making process to the bias of the decision-maker.	[25]
Sasmito	Several ventilation scenarios were tested to improve the ventilation system underground. The scenarios were tested by using simulation modelling software to develop strategies to improve the provided air quality and quantity. The advantages and disadvantages of each scenario were discussed, and the best scenario is based on the pressure drop and methane accumulation.	Weak cost-benefit analysis.	The decision method is only based on cost and non-numerical advantages and disadvantages.	[39]

All the studies shown in Table 1-2 used simulation software packages to simulate different scenarios and determine each scenario's impact.

Several of these studies used a simple method of cost-benefit analysis to establish which project is the most beneficial at the lowest cost. However, the decision-maker can still change the projects generated through the analysis since the decision-maker took non-numerical aspects into account, such as risk factors or implementation time, during the decision-making process. This aspect of the decision-making process opens it up to external motives and biases of the decision-maker.

A significant amount of decision-making time goes into deciding which projects should be considered and which projects will yield the best economic return and benefits. Although a mine is a business, and the main priority is to maximise financial return, the safety of the employees should also be one of the main priorities [40]. Thus, although deciding which project should be implemented is crucial for maximising economic benefit, it should not compromise safety [41].

Multi-criteria decision-making (MCDM) methods have assisted decision-makers in making the best choices when considering multiple criteria. The following section will thus elaborate on MCDM in the mining industry.

1.3 Multi-Criteria Decision-Making methods

MCDM methods assist in making structural choices that have multiple criteria and can evaluate objective (quantitative) and subjective (qualitative) conditions [42]. MCDM methods assist in structuring a scientific decision-making process while achieving the most accurate results by considering multiple decision criteria. MCDM methods can accommodate large amounts of data with different criteria during essential decision-making [43]. Yavuz [44] explained that MCDM problems consider only a single objective: selected from a list of projects to identify which alternative is the best fit.

The MCDM process consists of several methods, for example, The AHP-, PROMETHEE-, ELECTRE- and TOPSIS. Each method has a different purpose, which will be further explained in Table 1-3.

Table 1-3: MCDM methods with description

MCDM method	Definition
AHP (Analytic Hierarchy Process)	Use a pairwise comparison ¹ matrix to weigh the criteria' importance in contrast to each other [45].
PROMETHEE (Preference Ranking and Organisation Method for Enriching Evaluation)	Use outranking theory to determine the ranking of alternatives. Rank a finite set of alternatives using a pairwise comparison between the number of criteria [46].
TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)	The method picks the alternative closest to the positive ideal solution in the multi-dimensional computing space and the furthest from the perfect negative solution [47].
ELECTRE (Elimination and Choice Translating Reality)	This approach eliminates the alternatives that are not suitable due to problems and selects the best solution out of the rest [47].

Since MCDM methods have been successfully used during the decision-making process in different industries, this section will also critically examine these different studies. The different industries include renewable energy and power [48]–[52], machine learning [53], [54], cancer treatment [55] as well as business analytics [56], [57], investment management [58], [59] and the mining industry [60]–[62].

Sitorus et al. conduct a literature review of MCDM methods in mining operations and mineral processing [63]. Out of the 90 articles published between 1999 and 2017, 69 were related to mining, and the rest were related to mineral processing. The literature review's summary is shown in Table 1-4.

¹ Pairwise comparison – compare criteria to determine preference between each other [76]

Table 1-4: The results, relating to methods used, from the literature review [63]

Criteria	Application area	Percentage (%)
MCDM method	AHP	26 (18)
	TOPSIS	1.5 (1)
	Hybrid	46.4 (32)
	ELECTRE, VIKOR PROMETHEE,	5.8 (4)
	Other	23.2 (16)
Application for choice problems	Mining method selection	47.8 (33)
	Equipment selection	34.7 (24)
	Technology selection	7.2 (5)
	Site selection	7.2 (5)
	Other	3 (2)

Table 1-4 shows the diversity of the MCDM methods used in the mining sector to assist with the decision-making process. A hybrid of more than one MCDM method was used for most studies. Typically, one method was used to structure the selection process and determine the weighting of the criteria, and another method was employed to rank the projects [47].

1.4 The benefits of MCDM versus currently used methods

As mentioned above, currently, most mining projects use a simple cost-benefit analysis to assess project implementations. However, the methods have the following drawbacks:

- Cannot solve complex problems [43]
- Cannot consider outside factors [63]
- Struggle to incorporate effects of systems outside of those under review [64]
- Cannot only look at quantitative criteria [25]
- Cannot only solve for a single objective [49]
- Cannot decrease decision-makers bias [65]

The MCDM methods can structure the selection process and determine the weighting of the criteria. The reason MCDM methods is a better option:

- Allows researchers to structure complex decision problems [66]
- Incorporates subjectivity, experience, and knowledge [66]
- Easy to understand, and the process is logical [67]
- Normalise and subsequently aggregated data [67]

- Robust and flexible [68]
- Evaluates quantitative and qualitative criteria [69]
- Able to detect inconsistent judgement (inconsistency index) [42]
- Rank the most suitable alternative [63]

The characterisations above show why MCDM is one of the main methods used during the decision-making process.

1.5 Mine climate simulations

Simulations form a vital part of the design and optimisation of mine ventilation systems [70]. These simulations generally utilise data from a mine's Supervisory Control and Data Acquisition (SCADA) system and data management software [25]. Simulations can also be built based on data obtained from manual measurements if SCADA monitoring is unavailable [29]. The complexity of the simulations can vary from small-scale tests to holistic full-facility simulations [71].

The main benefit of these simulations is that they allow designers to test designs and implementations without costly real-world interventions [72]. This means that projects can be tested before implementation and the results of these simulated tests can be used as an additional decision-making factor.

When a full facility simulation is done instead of a local simulation, it can also allow decision-makers to consider the effect of intended projects or interventions on other portions of the operation.

The following section will expand on the literature on MCDM used in the mining sector and ventilation project selection.

1.6 Literature analysis

The literature analysis was done to establish how MCDM has been used in the mining industry and ventilation project selection. The analysis will entail doing a gap analysis of the literature to determine if the MCDM method has been used in the mining industry, especially during the decision-making process for environmental improvement projects. A critical literature study will follow from there, creating the problem statement.

To get a better understanding of what has been done relating to MCDM methods in the mining industry and project evaluation of environmental improvement projects, the literature on underground mines will be examined based on the following criteria:

- A) Does this study use 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 1-5 shows all the past literature on MCDM methods and project evaluation in the underground mining industry.

Table 1-5: Summary of the research literature review

Main author	Literature criteria			Reference no.
	A	B	C	
Acuña			x	[30]
Alpay	x			[73]
Ataei	x			[66]
Ali	x			[74]
Alpay	x			[75]
Amorocho	x			[76]
Asr	x			[77]
Baiden			x	[31]
Bascompta		x	x	[32]
Bitarafan	x			[78]
Bogdanovic	x			[79]
Balusa	x			[80]
Cheng		x		[33]
De Souza		x	x	[34]
Du Plessis		x	x	[35]
Du Plessis		x	x	[36]
Ebrahimabadi	x			[81]
Gupta	x			[41]
Ghazikalayeh	x			[82]
Hayati	x			[83]
Hudej	x			[84]
Iphar	x			[85]
Ibishi	x			[86]
Jamshidi	x			[68]
Javanshargiv	x			[87]
Kabwe	x			[88]
Kluge	x			[61]

Kizil	x			[89]
Karadogan	x			[90]
Kazakidis	x			[91]
Krog		x	x	[37]
Kursunoglu	x			[60]
Mackay		x	x	[23]
Maré		x	x	[92]
Mathews		x	x	[28]
Musingwini	x			[67]
Nel		x	x	[25]
Nourali	x			[62]
Owusu-Mensah	x			[93]
Özfirat	x			[94]
Peskens	x			[40]
Samito		x	x	[39]
Wang	x			[95]
Wang	x			[96]
Yavuz	x			[97]
Yavuz	x			[98]
Yavuz	x			[99]
Yetkin	x			[100]

The summary of literature relating to MCDM and environmental projects in Table 1-5 shows that none of the studies meets all the criteria related to questions A, B and C and very few of the studies met more than one. This shows that no study used MCDM methods to select the most suitable environmental improvement projects while using simulation software to analyse the project's impact.

Two studies had ventilation as one of the decision-making criteria during the mining method selection. Kluge [61] and Nourali [62] used ventilation as part of the decision-making criteria due to the mining method's impact on the mine's ventilation. They used the pairwise comparison to allocate weights to each alternative's ventilation impact. This is done to estimate how important ventilation is compared to the other criteria. However, no calculations or simulations were done to determine the impact of the mining method on the underground environment.

A more in-depth look at some selected studies from Table 1-5 will follow which elaborate on the literature's shortcomings. These two studies below focus on incorporated ventilation during the MCDM process.

Study 1

Title: Selection of an appropriate fan for an underground coal mine using Analytic Hierarchy Process

Author(s): N. Kursunoglu and M. Onder [60]

Industry: Underground mining

Options: Equipment selection – ventilation fan

MCDM: AHP

Overview: A MCDM method was used during the fan selection process. N. Kursunoglu used the AHP method to incorporate several criteria and simplify the complex nature of the selection process. The mines' haulage resistance was used to determine if the fan was the correct fit.

Shortcomings: The impact of the resistance on the haulage before the fan was calculated through first principle equations, which made the process tedious; limited options can be evaluated, and it is limited to a smaller area. Although fans are part of auxiliary ventilation equipment, the study did not calculate the impact of the fan on the more extensive holistic ventilation system, the up- and down- stream of the fan haulage.

Study 2

Title: Comprehensive and integrated mine ventilation consultation model - CIMVCM

Author: J. Cheng, Y. Wu, H. Xu *et al.* [33]

Industry: Underground mining

Options: Ventilation projects

MCDM: AHP

Overview: The study expands on the mathematical models used within the ventilation consulting computer model. The MCDM method, AHP, was used to allocate a reliability value to the subsystems of the mine's ventilation. The pairwise comparison scale was used to specify the five criteria' complexity levels. Other mathematical models, such as the Monte-Carlo simulation, were then used to evaluate the ventilation system and assist the occupational hygienist in selecting the best ventilation plan.

Shortcomings: The AHP method was not used during the selection process, but a reliability factor was determined that clarifies if the ventilation system is adequate. The implementation cost of the ventilation system was not considered during the evaluation process, only the fan's running cost. In conclusion, the authors mentioned that this consultation

method would not wholly model the ventilation system, which shows that the simulation model does not fully characterise the ventilation system and that the holistic system was not simulated.

The following studies expended on the two papers about selecting the best ventilation project.

Study 3

Title: Efficient use of energy in the ventilation and cooling of mines

Author: J. du Plessis, W.M. Marx, and C. Nell [35]

Industry: Underground mining

Options: Ventilation and cooling projects

MCDM: None

Simulations: Yes

Overview: The paper discusses implementing two strategies; load clipping and load shifting. The main motive behind the projects is to reduce the energy usage of cooling and ventilation systems. Simulation network modelling was incorporated to optimise the system based on energy-saving initiatives. The optimal scenarios could then be simulated to choose the most energy-efficient system with proper workplace conditions.

Shortcomings: Du Plessis did not elaborate on the decision-making process, but the paper aimed to obtain the most energy-efficient system, which is a cost-benefit analysis, as it was the only two variables used to decide which project would be the best option.

Study 4

Title: Evaluating complex mine ventilation operational changes through simulations

Author: A. Nel, J.C. Vosloo and M. Mathews [25]

Industry: Underground mining

Options: Ventilation and cooling projects

MCDM: None

Overview: The study developed a scalable method to evaluate and optimise ventilation projects using simulation software. The key performance indicators (KPIs) were based on service delivery and operational energy cost.

Shortcomings: The method to evaluate and optimise the projects was sufficient, but the best solution to improve the operational efficiency (energy savings) was still made at the decision-maker's discretion. The method showed that one of the projects would have the best impact but was not selected in the end based on a non-numerical risk assessment. The method opens the decision-making process to the bias of the decision-maker.

The studies above showed how the MCDM process had not been used during the selection process of ventilation projects, and the current process involves selecting the most suitable project only based on the benefit, cost, and the decision maker's discretion. During the decision-making process, no explicit strategy incorporated the other criteria, such as risk, which is a non-numerical attribute.

This means that research should be consulted to know if a non-numerical attribute like risk was previously used during the MCDM process and can be used for underground projects. The study below shows how MCDM methods rank risky areas after an earthquake.

Study 5

Title: **A two-level interval valued neutrosophic AHP integrated TOPSIS methodology for post-earthquake fire risk assessment: An application for Istanbul**

Author: P. Gulum, E. Ayyildiz and A. Gumus. [101]

Industry: Risk reduction

Options: Districts

MCDM: AHP and TOPSIS

Overview: The secondary disaster after an earthquake can cause further harm, and fires can cause severe damage. The MCDM was used to assist in determining the risk assessment of the different districts affected by the earthquake. AHP with interval-valued neutrosophic (IVN) estimated the criteria weights, while TOPSIS was used to rank the districts based on the fire risks.

Conclusion: MCDM, incorporated with risk assessment criteria, functions as a valuable tool to organise risk problems, which will assist in focusing on the most critical problems without dividing precious resources into too many different tasks that might result in not completing any tasks.

This study is an example of how risk can be incorporated during decision-making and can be used as a building step to develop a method that can include non-numerical attributes during the decision-making process.

The above studies elucidate the need to use MCDM methods in cooling and ventilation projects for underground environmental improvements. The successive section will thus elaborate on the identified problem statement and the study's objectives.

1.7 Problem statement

The shortcomings from the literature, shown in Table 1-5, identified the following problems:

- Decision-makers of operational deep-level mines do not have a scientific decision-making method that can handle the complexity of multiple criteria to evaluate and select the most suitable ventilation and cooling projects.
- Although MCDM methods are widely used in the mining method selection, they were not used during the holistic ventilation project selection process.
- MCDM methods have not been combined with ventilation simulations to predict the impact of proposed projects on the mine's complete and integrated ventilation system.

No method uses MCDM methods in combination with simulations during the evaluation and selection of the ventilation and cooling projects.

1.8 Study objectives

Through the above problem statement, the objectives of this study are as follows:

1. Develop a method to assist decision-makers of operational deep-level mines in evaluating projects based on multi-criteria and ranking various environmental improvement projects.
2. Incorporate MCDM methods to rank the various environmental improvement projects.
3. Integrate ventilation simulations with MCDM methods to evaluate the entire mine's holistic ventilation system.

The identified objectives provide the basis for the novel contributions of this study. The following sections elaborate on the novel contributions.

1.9 Novel contributions

The proposed method will be developed in two sections to address the problem adequately. Figure 1-7 shows the proposed method outline to indicate the novel contributions.

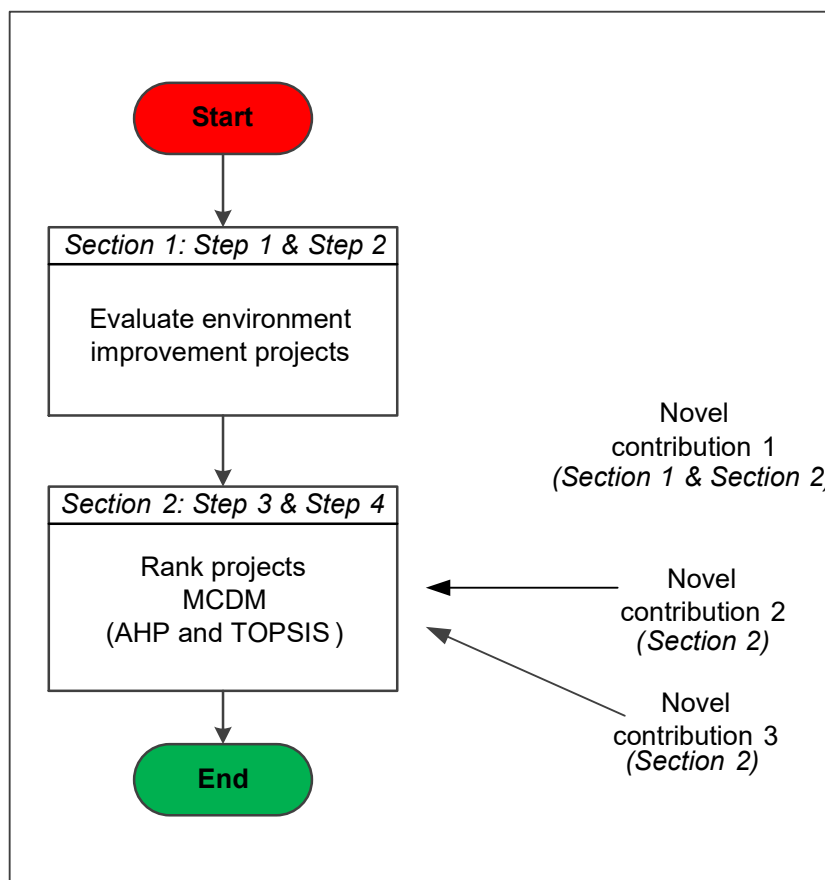


Figure 1-7: Proposed method outline to indicate novel contributions

The proposed method outlined in Figure 1-7 shows that the first section of the methodology will evaluate the projects in an operational mine, while the second section will rank the projects. Novel contribution 1 is the entire proposed method (Steps 1-4) to evaluate and rank the environmental improvement projects. Novel contributions 2 and 3 fall into section 2 of the method, which ranks the projects.

More detail on each novel contribution is explained below, with Table 1-6 as a summary at the end.

1.9.1 Novel contribution 1

Developing a method that evaluates and ranks various environmental improvement projects in operational deep-level underground mines.

Novel contribution 1 refers to the complete method indicated in Figure 1-7.

What needs to be done?

A method needs to be developed to assist mining personnel in evaluating environmental improvement projects in an operational mine and ranking these projects using a scientific multi-criteria decision-making method.

How is it currently done?

The current methods assist the mine personnel in evaluating different ventilation and cooling projects identified by the mine, as seen in Table 1-2. These methods evaluate the projects based on two criteria, usually project impact and implementation cost. The comparison happens between two or three projects of the same system, ventilation, or cooling. The most suitable project is chosen based on the preference of the decision-maker, usually the financial manager that favours economic benefits.

Why is this insufficient?

The evaluation criteria are limited, as the decision-maker cannot compare multiple criteria. The criteria are mostly limited to cost and impact (benefit). The quantity of projects is limited to only two or three projects compared to one another.

Nel [102] the author of “*Mine ventilation characterisation through simulations*” noted in the studies’ recommendations for further research that a method should be developed to evaluate and optimise other mining systems excluding ventilation, as done through his research.

Only one system’s projects are evaluated; projects that increase airflow or increase cooling are compared to each other. Many projects that can improve the underground environment are excluded from the evaluation.

The final decision depends on the decision-maker’s preference, as it can be manipulated to fit the decision-makers agenda. The ventilation custodian will favour the ventilation impact, whereas the financial manager will favour the economic benefit, as done in Nel’s study [25].

How does this study solve the problem?

This study will solve the above-outlined problem by developing a method that will assist the decision-maker in evaluating and ranking a range of projects that can improve the underground environment of a deep-level mine. These projects will then be evaluated and ranked to identify the most suitable solution through a method that considers all criteria. The ranking of the various projects will assist the mine in focussing resources on the most suitable project.

1.9.2 Novel contribution 2

Use multi-criteria decision-making (MCDM) methods to rank underground environmental improvement projects.

Novel contribution 2 refers to a subsection of the second section of the method, ranking the projects of the method indicated in Figure 1-7.

What needs to be done?

A scientific decision-making tool needs to be incorporated into the method to rank the most suitable environmental improvement project based on various evaluation criteria, which will reinforce the decision-making process of the method.

How is it currently done?

As seen in Table 1-2, column 3, none of the studies use a formal decision-making method to establish which of the environmental improvement projects compared will be the most suited. Table 1-5 also highlights this, where decision-making methods have been used in the mining industry, especially with mining method selection but not for selecting ventilation and cooling projects.

This study shows that the decision process is limited to the decision-maker's capabilities, experience, and field. Most projects use cost-benefit analysis and exclude essential criteria, while some criteria are only included as notes that need to be acknowledged when making the final decision, as seen in Nel's study [25].

Why is this insufficient?

Not using a scientific decision-making method makes the process dependent on the decision-maker's experience and judgement, leaving the process open to partiality. A deep-level mine's primary purpose is increased productivity with maximum safety, and this should be incorporated during the decision-making process and not only as a note at the end of the evaluation process. The evaluation process only considers the economic benefits and project impact, but the safety and risk, as non-numerical values, are excluded.

How does this study solve the problem?

An MCDM method will be used during the environmental improvement decision-making process to assist the decision-maker when deciding on the most suitable project. The MCDM methods can incorporate subjective and objective criteria with no limit on the number of criteria used during the process.

A combination of two MCDM methods will be incorporated to structure the process and rank the projects. The first MCDM method will establish and fix the criteria weight, while the second MCDM method will rank the projects according to the project suitability. These ranked projects will assist the personnel in focussing time and resources on the correct solution.

1.9.3 Novel contribution 3

Using ventilation simulations in combination with MCDM methods to evaluate and prioritise the impact of each project on the complex underground ventilation system.

Novel contribution 3 refers to a subsection of the second section of the method and adds simulations to evaluate the holistic impact of the potential projects, with MCDM in the method, as indicated in Figure 1-7.

What needs to be done?

Ventilation simulations should be integrated with the MCDM method to evaluate the effect of environmental improvement projects on the mine systems. The project's impact on the holistic ventilation system should thus be evaluated using ventilation simulations during the decision-making process.

How is it currently done?

During the mining method selection, Kluge [61] and Nourali [62] used ventilation as one of the evaluation criteria. The impact of the mining methods on the ventilation was not based on calculations but on experience from previous interactions with that mining method. In the ventilation equipment selection article by Kursunoglu [60], the system impact was made by first principle calculations. One study, Yavuz [99], used simulations during some mining method selections to indicate the underground rock formations. Table 1-5 showed that no study used climatic simulations with MCDM methods.

Why is this insufficient?

Using hand calculation during the project selection process means that the exercise will be tedious, limited, and lengthy if the whole ventilation system with different projects needs to be evaluated. Several authors, such as Mathews [28], De Souza [34] and Fair [103], have indicated over the last decade that the only way to evaluate ventilation systems is through ventilation simulations, and this is because a mine's ventilation system is integrated and complex.

How does this study solve the problem?

This study includes ventilation simulations to determine the impact of ventilation improvement projects when using MCDM methods as a decision-making tool and will allow outside stimuli and

effects to be considered while further improving the accuracy of the MCDM method when used for environmental improvement projects on deep-level underground mines.

The summary of the novel's contribution to literature is shown in Table 1-6.

Table 1-6: Novel contributions summary

Currently done	Why insufficient?	This study solves the problem
Novel contribution 1: Develop a method that evaluates and ranks environmental improvement projects.		
Evaluation criteria limited	Decision-makers cannot compare multiple criteria. Mostly benefit and cost.	Evaluate multiple criteria scientifically with added checks for consistency.
Only one system's projects are evaluated	The decision-maker either evaluates ventilation or cooling projects, which excludes projects from the evaluation.	The method enables cooling and ventilation projects to be evaluated simultaneously to improve the underground environment.
Limited variety of projects	Not all the possible projects are evaluated because of limited capabilities, which can entail missing the top project.	The methods do not limit the number of studies to be evaluated.
Preference of the decision-maker	The current processes open the final decision to the decision-maker's discretion.	The criteria and importance are determined through literature and fixed before the evaluation process.
Novel contribution 2: Use MCDM methods to rank projects underground improvement projects.		
No scientific method to select the most suitable project	Decision-maker's preference for the final decision can be manipulated to fit the decision-maker's agenda. No structure with difficult-to-scale processes.	MCDM is a scientific method that structures, and rank the project based on subjective and objective criteria. Criteria weights are fixed before through the AHP method.
Novel contribution 3: Combine ventilation simulations with MCDM methods to evaluate projects.		
No climatic simulation software used with MCDM methods	Limited, tedious, and lengthy processes without evaluating the complex system. The holistic ventilation and cooling system cannot be evaluated without simulations.	The evaluation of the holistic underground environment is incorporated with the MCDM method. Increase the accuracy of the decision-making.

The following chapters will elaborate on the novel contributions listed above, and these three contributions will be satisfied at the end of this study.

1.10 Study outline

This study will follow the case study methodology to define a problem, develop a solution through literature, and analyse a case study to validate and discuss [104]. Figure 1-8 shows the outline of the global case study's research methodology that corresponds with this thesis.

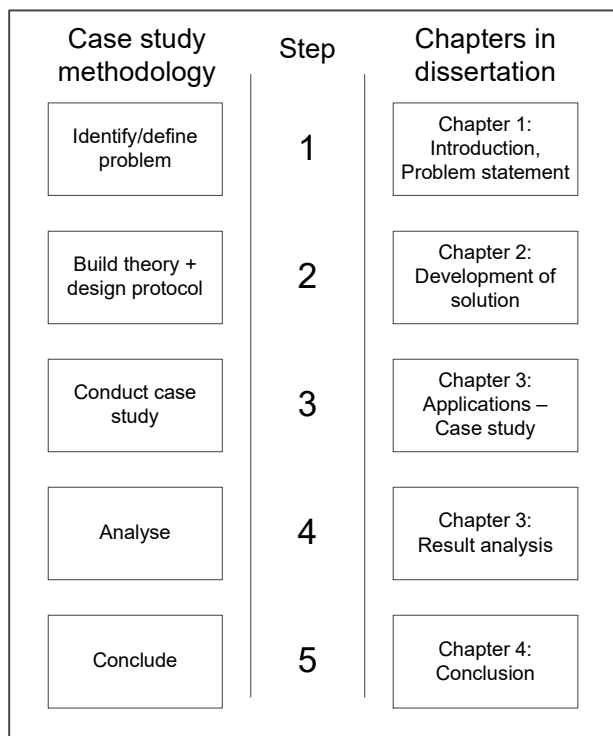


Figure 1-8: Research methodology alignment with thesis layout (Adapted from [104])

The following section will expand on Figure 1-8 and describe each chapter of this thesis.

Chapter 1: Introduction to mining project selection

Chapter 1 gives a background on underground mining and project selection, followed by further expanding into the MCDM process, and by a critical literature study. An apparent problem is identified through the literature study, as seen in Figure 1-8's Step 1.

The study's objective derived from the problem statement, and the novel contributions of this study to research, are also explained in Chapter 1.

Chapter 2: Development of a new ranking method

Chapter 2 uses literature to develop the method used on mines to evaluate and rank the environmental improvement projects. Chapter 2 corresponds with the research methodology's Step 2 in Figure 1-8.

Chapter 3: Applications and Results

The method is then applied to a case study in Chapter 3, as stated in Figure 1-8's Step 3. The case study verifies that the method is working and sufficient to evaluate and rank the projects. Step 4 of the research methodology analyse and interpret the results from the applied case study.

Chapter 4: Conclusion and recommendations

Step 5 of the research methodology in Figure 1-8 is the conclusion. In Chapter 5, the study will be concluded through an overview of the whole study while ensuring the objective and novel contributions of this study are satisfied. The main points of the study will also be highlighted, and future recommended work will be discussed in this chapter.

1.11 Conclusion

Gold mining production in South Africa is decreasing while mining costs are increasing due to various aspects. Therefore, a robust decision-making process is essential when deciding on the most suitable project for improving operational mines' underground environment. Literature indicates that MCDM methods are used in the mining industry to select the best mining method because MCDM evaluates decision problems in a structured and impartial manner. The literature falls short in that no current method exists to evaluate and rank environmental improvement projects. Concurrently, MCDM methods have not been used in decision-making to rank ventilation and cooling projects. Even further, during ventilation equipment MCDM problems, the impact on the ventilation was not estimated using ventilation simulations.

This study's novel contributions to literature will develop a method to evaluate and rank various environmental improvement projects in operational deep-level underground mines. Combined with applying MCDM methods to assist in the decision-making process and ranking of the projects, the third novel contribution will be incorporating mine ventilation simulations in the evaluation process of the MCDM method to determine the impact of the various projects.

The following chapter will develop the method to evaluate and rank environmental improvement projects.

2. DEVELOPMENT OF A NEW RANKING METHOD

2.1 Preamble

In Chapter 1, it was established that a method to evaluate and rank various environment improvement projects is required. In this chapter, a method will be developed through consulting various research studies to satisfy the study's objectives.

The method is developed to assist the mining personnel in evaluating various projects during the pre-feasibility or LOM planning stage to improve the underground thermal conditions. These ranked projects assist the personnel in focussing precious resources on the correct solution. Figure 2-1 shows the steps to evaluate and rank the projects.

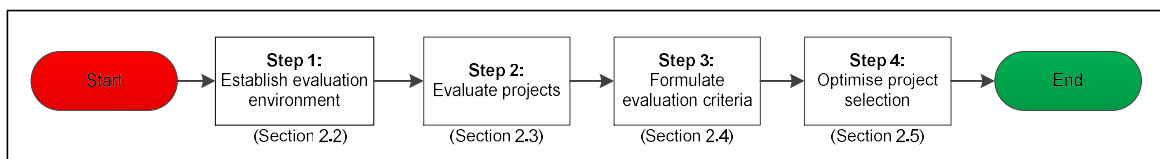


Figure 2-1: Project evaluation and ranking method

The following sections will elaborate on each step of the project ranking method. The mine needs to improve the underground environment but is unsure which project will suit its needs. By implementing the method in Figure 2-1 and following each step, the mine will be able to select the most suitable project. Step 1 (Section 2.2) establishes the evaluation environment. Step 2 (Section 2.3) evaluates the identified projects and collects all the information required for the next steps to rank the projects. Step 3 (Section 2.4) structures and weighs the evaluation criteria using an MCDM method, and Step 4 (Section 2.5) ranks the projects.

Figure 2-16 shows the complete method to evaluate and rank projects with the phases in each step as shown in Figure 2-1.

2.2 Step 1: Establish evaluation environment

The main aim of Step 1 is to start creating the boundary of the investigation. Establishing the goal of the investigation is the next phase of this step, and a clear target should be accomplished after the method is implemented. After the boundary and the goal of the investigation are set, information should be collected which will enable the baseline development and the simulation model used during the evaluation phase. The last phase of this step is to create a list of all the projects that can possibly improve the underground environment.

This step consists of five phases that will produce the necessary information to evaluate the projects in the following step. Figure 2-2 shows the phases of Step 1 discussed in this chapter.

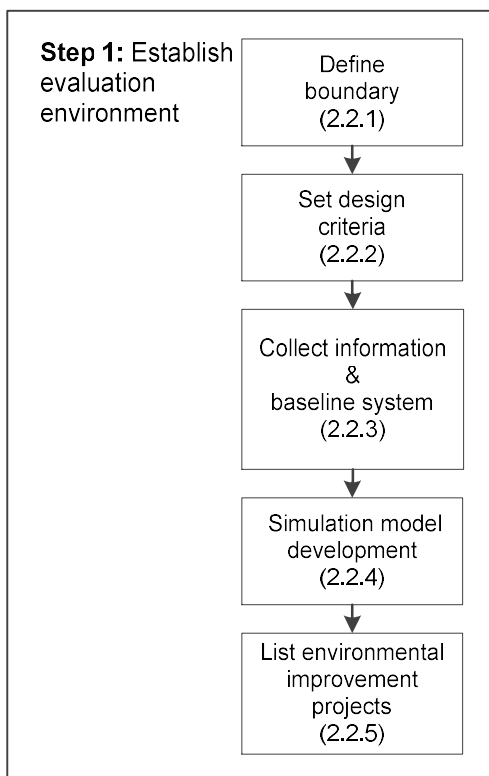


Figure 2-2: Five phases of Step 1 of this method

2.2.1 Define the boundary

Defining the boundary for the investigation is crucial to ensure the focus is in the right area [72], [105]. The selected boundary should include the investigated area and the factors that influence the conditions of the specific area. The boundary can be only a section of a mine, for example, “one level” or multiple mines. Figure 2-3 shows an example of a typical boundary selected for a mine.

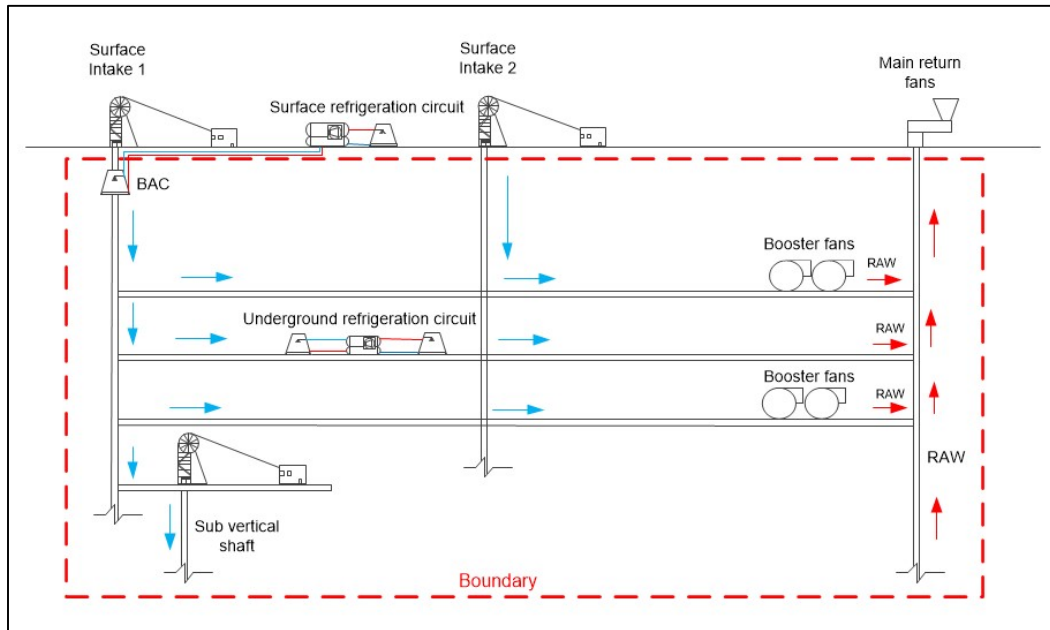


Figure 2-3: Schematic of the typical boundary selection

2.2.2 Set design criteria

Setting the design criteria is to ensure that there is a good working environment underground. The design criteria are developed from the regional requirement and corporate policies [106], [107].

The ventilation requirements are based on three mine contaminants: heat, dust, and gasses, but diesel particulate matter (DPM) is included for mechanised mines operating with diesel machinery [108], [109]. The requirements to remove heat from the environment will typically surpass the requirement of the other three contaminants in a deep-level mine [108], [110].

The design criteria for the intake temperatures and velocities are set to ensure that the temperatures inside the working areas do not exceed the legal temperature requirements, as shown in Table 1-1, prescribed in the Mine Health and Safety Act (MHSA), 1996 (Act No 29 of 1996).

During deep-level mines ventilation system design, numerous studies indicated that air cooling power (ACP) could be used as a heat stress index as ACP considers both the airflow velocity and wet-bulb temperature [20], [24], [110]. ACP indicates air's cooling ability through different wet-bulb temperature and air velocity combinations [20]. An ACP of 250 – 300 W/m² is used during the designing phase to ensure adequate ventilation is distributed to the working areas [20], [25], [110]–[112]. The ACP is calculated by using

Equation 2-1.

Equation 2-1: Calculating air cooling power [113]

$$k = (14.65 + 35.59 \times \sqrt[3]{v}) \times (36.5 - T_w) \quad v < 1 \text{ m/s}$$

$$k = (4.19 + 46.05 \times \sqrt[3]{v}) \times (36.5 - T_w) \quad v > 1 \text{ m/s}$$

Where:

k = Air cooling power (W/m^2)

v = Velocity (m/s)

T_w = Wet-bulb temperature ($^{\circ}C$)

Although the requirements to remove heat will be the most significant value, ACP is a good value for the design criteria because the design requirements of the other three contaminants can also be incorporated into this value.

At the end of the investigation, the design criteria should be revisited to ensure the implemented project is successful.

2.2.3 Collect information and baseline systems

This phase of Step 1 is to collect all the information from the mine and baseline the current underground conditions. The projects will be compared against the baseline during the evaluation in Step 2.

(i) Collect information

Information collection include obtaining the layouts from the planning department, and ventilation audits from the ventilation department [72]. Information can also be collected from a central system called the Supervisory Control and Data Acquisition (SCADA) system that has all the measured data [25]. Table 2-1 shows all the information required, where it will be found and used.

Table 2-1: Information required and departments

Information	Description
Mine plans	The mine plans show the layout, and the depth of the level underground, with the working areas indicated. The mine plans mainly indicate the haulage size, workshops, electrical equipment, and infrastructure. These plans are collected from the mine's planning department in drawing exchange format (DXF).
Airflows plans	The airflow direction and the quantity of air are indicated on the airflow plans. The mine's ventilation department develops the air flow plans through airflow surveys.
Velocities	The velocities of air at the intakes of the levels are necessary as it is used to calculate the ACP. The velocity information can be collected at the ventilation department or the SCADA system, if instrumented.
Intake temperatures (wet- and dry-bulb)	The air's wet-bulb temperatures at the intakes are vital as it is used to calculate the ACP. The temperature information can be collected at the ventilation department or the SCADA system, if instrumented.
Return temperatures (wet- and dry-bulb)	The return temperatures will be used during the simulation model development. The temperature information can be collected at the ventilation department or the SCADA system, if instrumented.
Barometric pressure	The barometric pressure influences the air's characteristics and is considered when the simulation model is built.
Cooling capacities	The cooling infrastructure's information and capacities should also be collected as this significantly impacts the air's cooling capabilities.
Fan specifications	Fan specification is essential to ensure the correct quantity flows through the mine. Most simulation software can insert the fan curves as an input.

The information in Table 2-1 will be used to develop the baseline and the simulation model.

(ii) Baseline system

Baselining the system will give a foundation against which the possible projects can be assessed [114]. The baseline set-up in this phase will assist in developing the simulation model and be used during the project evaluation as the reference.

Baselining the underground environment involves identifying the locations at which the projects should meet the design criteria and will be evaluated. These locations should be selected at the level and workplace entrances, this will give a good indication of how a project will improve the underground conditions. The ACP should be calculated at these locations as this will be used during the evaluation.

The cooling infrastructure's performance should also be baselined during this stage.

After this phase's aim is accomplished, all the information should be collected, and the whole system; underground environment and cooling, should be baselined. This baseline system will now be used during the next phase to develop the simulation model of the mine.

2.2.4 Simulation model development

The best way to evaluate the complex and integrated systems of deep-level mine ventilation and cooling systems is through simulation software packages. Using simulation-based models is the only way to thoroughly evaluate the holistic ventilation system [34], [103].

(i) Simulation software

A wide range of simulation software is available that can be used to simulate ventilation and cooling systems. The simulation software includes Vuma 3D [115], VentSim [105], [116], Environ [38], Flownex [38] and Process Toolbox (PTB). PTB is used for this method since it can solve complex and integrated cooling and ventilation systems, as shown through studies done by Mathews and Mare [28], [38].

Process Toolbox is a thermohydraulic simulation software that can solve energy-, mass- and momentum- balances as steady-state or transient solutions [71]. The transient flow solution is solved through quasi-steady-state and semi-implicit algorithms to present the changes over time [105].

PTB has a component-based, three-dimensional (3D) graphical user interface (GUI). The software is developed with ease-of-use in mind, by dragging-and-dropping components and has a library containing predefined components to configure the required elements [103]. The actual digital layouts, the DXFs from the mine can be imported to develop an accurate 3D replica of the underground network [38]. Figure 2-4 shows the GUI of PTB and the 3D ventilation capabilities.

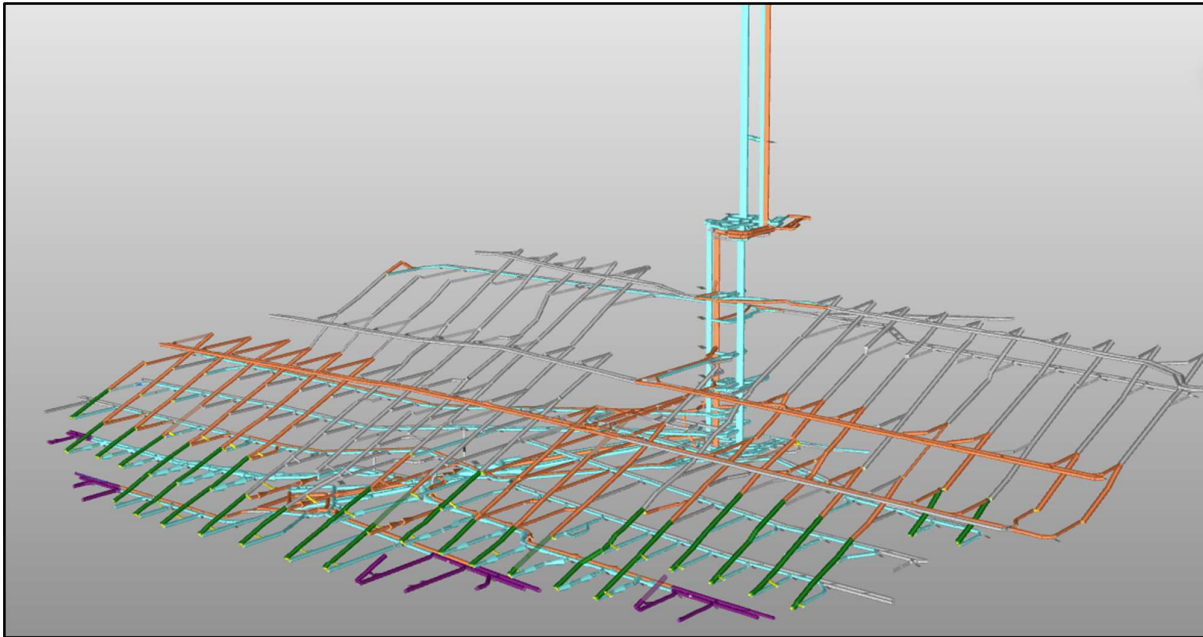


Figure 2-4: Representation of the 3D GUI of a ventilation network

All the predefined thermohydraulic components in PTB are shown in Figure 2-5.

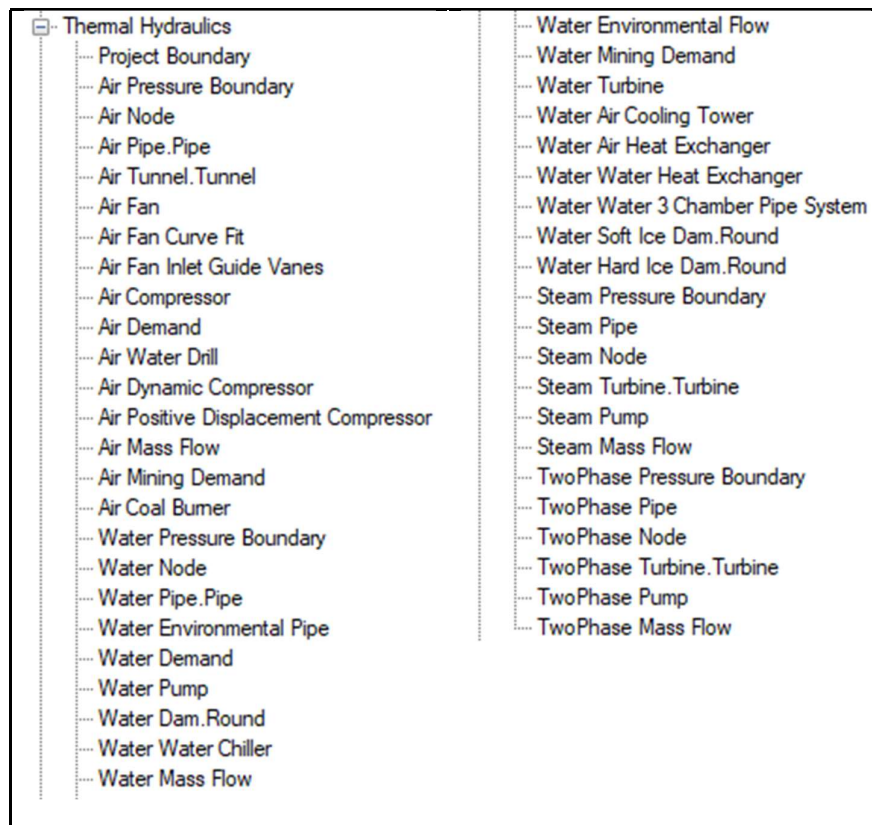


Figure 2-5: PTB thermohydraulic components

Figure 2-5 shows that the entire ventilation and cooling network can be developed through the predefined components. PTB has additional built-in functions to improve the simulation software's usability, as seen in Figure 2-6.



Figure 2-6: PTB's additional capabilities

The additional capabilities' functions are:

- Simulate (A): Start the simulating process.
- Power (B): Determine the simulation power usage of the energy management strategy.
- Heat load (C): Determine the heat load of the model.
- Compare (D): Compare different simulations models or configurations.
- Properties (E): Establish the number of steps or period the simulation should run.
- Database (F): All the models and information can be loaded onto a central database to improve accessibility.
- Motion (G): Simulate the underground logistic environments like cages, locos, employees walking.

(ii) Calibration

Calibration is the process of replicating the ventilation and cooling network in the simulation software to a defined accuracy. Mathews developed an integrated dynamic simulation approach that can be used for mine cooling system planning, while Nel developed a method to evaluate operational ventilation changes using simulations [25], [28]. Figure 2-7 shows the steps to build and calibrate a ventilation simulation model.

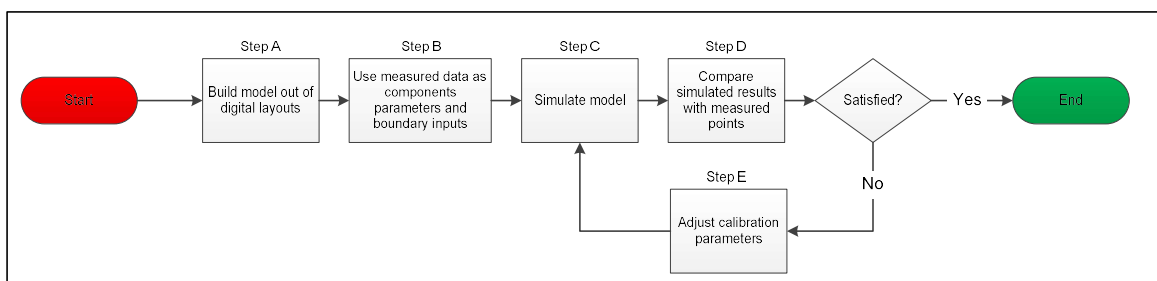


Figure 2-7: Steps to build and calibrate a ventilation simulation (Adapted from [103])

Figure 2-7 shows that Step A is building the wired network using the mine plans, as explained in Table 2-1. In the following step, Step B uses the airflow plans and the baseline to start calibrating the model that will duplicate the underground system. Step B inserts the information collected

through the plans and audits into the boundary components. Step C simulates the model and show the model replication of the current underground conditions.

The accuracy of the model is an important part, which is part of Step D. The actual measurements are compared to the model to determine if the model is an accurate representation of the underground environment. If the model developer is not satisfied with the accuracy, the developer should adjust the calibration parameters in Step E and return to Step C. The accuracy will be discussed in more detail in the next sub-section.

In Step E, adjustments to the friction coefficient, door fraction, wet area fraction and heat factor should be made to increase the simulation software's ability to reproduce the plan. Figure 2-8 shows the calibration parameters where most of the changes should be made when calibrating the simulation model using PTB.

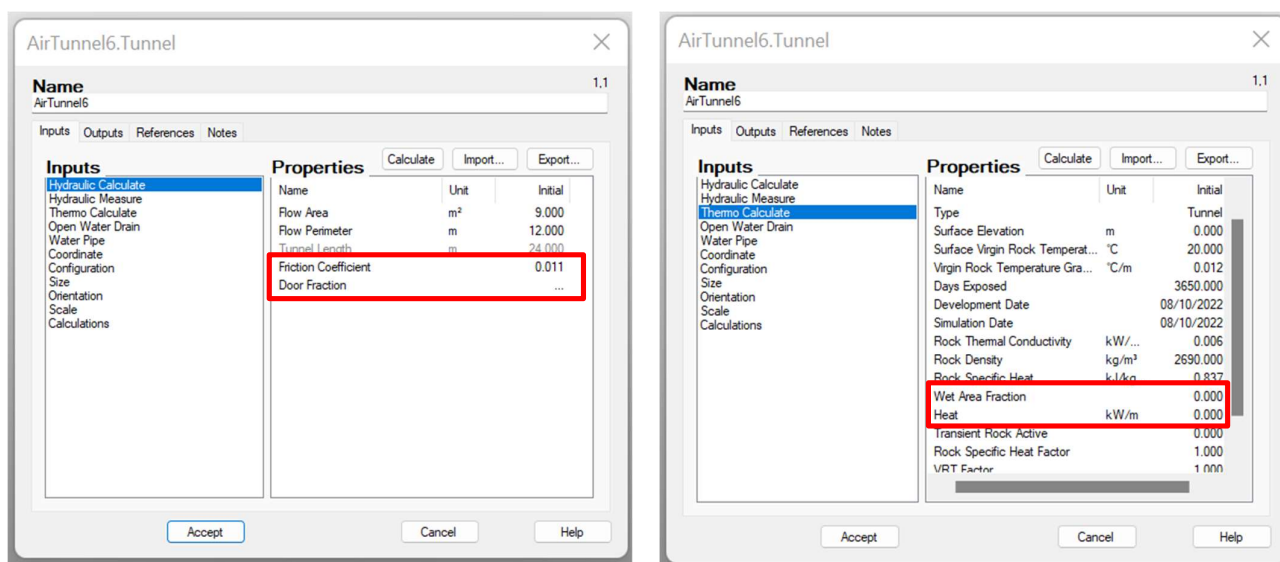


Figure 2-8: Calibration parameters: Air tunnel input interface changes

This is an iterative process until the developer is satisfied with the level of accuracy. The level of accuracy will be discussed below.

(iii) Accuracy

Step D is determining the accuracy of the model. During the development of a simulation, three requirements conflict with each other; stability, rapidness, and accuracy [117]. A compromise should be made depending on the goal of the simulation [117].

Mare indicated in his study that the more time and money spent on calibrating the model, the fewer errors there should be in the model [38]. During the pre-feasibility study stage, the model should be simplified to decrease the time spent on developing the model. Studies indicated that a model accuracy of 95% is acceptable in the mining sector but also mentioned that it took up to three years

to develop and calibrate [38], [105]. Should the collected data be reliable, some minor adjustments to the factors shown in Figure 2-8 will render the model a representation of the underground environment [118].

The model's accuracy is determined by calculating the average of the percentage errors between the measured value and the simulated result. Equation 2-2 calculates the percentage error at an identified point.

Equation 2-2: Calculate the simulation percentage error

$$\%E = \frac{|y_s - y_m|}{y_m} \times 100$$

Where:

$\%E$ = Percentage error (%)

y_s = Simulated result

y_m = Measured value

Equation 2-2 should be used to calculate the error percentage for the mass flows, wet- and dry-bulb temperatures. The percentage error will be calculated at the intake and return of levels, shafts, haulages, and chill ponds. The project evaluation points identified in the baseline should also be included in these points. The average mass flows, wet- and dry-bulb temperatures are then calculated to give the model accuracy. Should the model's accuracy be acceptable, the model can then be used as a viable tool to predict the impact of the proposed projects on the underground environment [119].

Should other simulation software be used during this method, some of the above descriptions will change because each software has its own way of building a ventilation and cooling model.

The underground system is now baselined, and a simulation model has been developed to simulate different scenarios that can improve the underground environment [25]. The model will serve as the primary model, and the scenarios will be "implemented" on this model; this means that it is not necessary to redo this phase for each project.

The next phase of Step 1 is to list all possible projects that can be implemented to improve the underground environment.

2.2.5 List environmental improvement projects

During this phase of Step 1, the engineers and the occupational hygienists of the mine will need to compile a list of all the possible projects that can assist in creating acceptable underground

environmental conditions to align it with the design criteria. Through literature, this section supports the decision-makers with ideas for projects to improve ventilation and cooling.

The underground environment can be improved by either improving the ventilation in the working areas, adding additional cooling, or reducing the heat sources. To rectify an issue based on the airflow, the possible solutions will be grouped under the sub-title *Ventilation*. The possible solutions related to cooling infrastructure will be grouped under the sub-title *Cooling*.

(i) *Ventilation*

More air needs to be moved through the mine to improve the ventilation of the mine [24]. This can be done by decreasing the frictional resistance of the network or by increasing the airflow area. Table 2-2 contains possible issues and solutions to rectify the problems.

Table 2-2: Possible issues and examples of ventilation projects

Issue	Possible solutions	Explanation	Ref.
Intake and return airflow quantities do not add up.	Close leaks	Closing off abandoned areas and resealing deteriorated seals will decrease the possibility that air will escape through these areas and improve sealing capabilities.	[24]
Not enough air to supply the mine.	Increase haulage size	Increasing the haulage size reduces a haulage's resistance and makes airflow easier.	[120]
	Ventilation-on-demand (VOD)	Air is supplied to working places when there is work done in the area; otherwise, the quantity of air is restricted.	[30]
	New haulages (intake or return)	A new path for air to flow without resistance in the airway will reduce the friction resistance of the intake or return system.	[24]
	Removing resistance	Deterioration of the airway increases the flow resistance. Remove unplanned waste, obsolete equipment, and FOG.	[110]
	Additional fans	Extend the reach of the existing ventilation network to contribute to extracting air from the mine.	[120]
	Controlled reticulation	Air from the working places gets redistributed into the intake air after already being used.	[121]

Table 2-2 can be used as a guideline to check if these ventilation solutions will assist in fixing the issues discovered during the system evaluation. The examples in Table 2-2 are not the only ventilation initiative in the mining industry; many variations exist. The main objective is to increase the quantity and quality of fresh air to the working areas.

(ii) Cooling

Many cooling projects can be introduced at the different stages in the mine, for example, Figure 1.4 shows some of these hierarchy steps. Some mines left out these steps and never installed the cooling infrastructure due to cost constraints [122]. Table 2-3 shows possible issues and solutions to rectify the problems.

Table 2-3: Possible issues and examples of cooling projects

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 there are fewer losses to the surroundings.	[18]
Not enough cooling infrastructure	Surface cooling	Send ultra-cool air down the downcast shaft.	[23]
	Cold water from the surface	Pipe cold water underground for secondary cooling closer to the working areas.	[123]
	Underground refrigeration	Cool the water underground to use for underground bulk air cooler (BAC), operational water and tertiary cooling.	[124]
	Ice from surface	Send ice underground in ultra-deep mines to use as cooling.	[124]

Table 2-3 can be used as a guideline for possible cooling projects to improve the underground environment. The examples shown in Table 2-3 are not the only cooling initiative in the mining industry, many variations exist.

The last phase of Step 1 should give the decision-makers, the engineers, and occupational hygienists a list of projects to evaluate in the next step. After Step 1 is completed, the decision-maker should have a baseline, simulation model and a list of projects that will be used in the next step to evaluate the projects.

2.3 Step 2: Evaluate projects

Step 1's list of projects will be evaluated in Step 2 of the method. The evaluation of the projects will collect all the information that will be used in the next two steps to rank the projects. At this point, the evaluation criteria are established, backed by literature, and will assist in making an informed decision to improve the underground environmental conditions.

Criteria

Table 1-2 shows that most projects are evaluated using two criteria during the decision-making process: the impact of the project and the project cost, also called a cost-benefit analysis. A balance

between safety and cost should be maintained to implement a good ventilation plan [39]. Another aspect that needs to be considered is the project's energy efficiency [34] and implementation time. The reason for deciding on these five categories is as follows:

Risk mitigation: Dehghani [125] stated that the results would be invalid if a project is evaluated without considering the risk of future losses. Du Plessis [36] and Nel [25] also attempted to include risk during project evaluation.

Impact: The project needs to have a positive impact on the underground environment and be evaluated to understand if the impact is sufficient to implement the project [24], [30], [34], [36], [39], [92].

Cost: A mining company is a business, and many different role players invest large sums of money at start-up to generate returns on investments later. In this economic climate, much care is required to ensure that the project is cost-effective before spending large sums of money [34], [36], [102].

Energy efficiency: The power usage of the projects should be included since the cost of power for deep-level mining is becoming more expensive due to the exponential increase in electricity costs [126].

Implementation time: Implementation time needs to be included in the evaluation criteria because the faster the implementation time, the quicker the risks' probability will decrease. This will also assist in adding the possibility of tackling the low-hanging fruit at the start [36].

These criteria are used to develop Step 2 to evaluate each project. Figure 2-9 illustrates the evaluation quantification steps associated with Step 2.

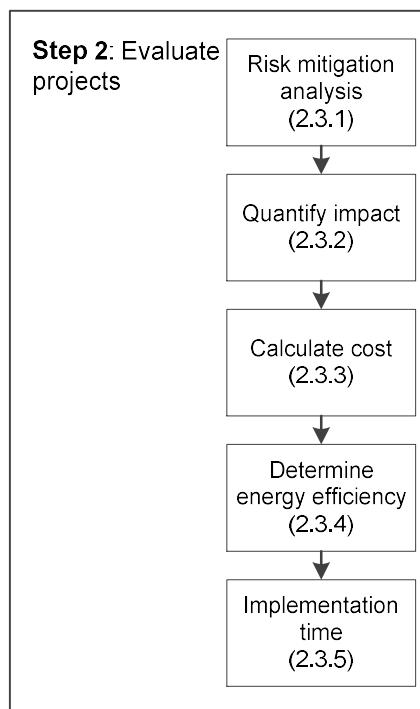


Figure 2-9: Five evaluation criteria of Step 2 of the method

2.3.1 Risk mitigation analysis

Risk in this context refers to what impact the implementation will make by mitigating or diverting a risk that presents itself in the future [122], [127]–[129]. During this part of the evaluation, the decision-maker needs to determine if the project is implemented, does the project prevent an event that will interrupt mining activities. These mining activities refer to production and blasting activities.

The challenge is that risk is difficult to incorporate during decision-making since it is not easy to express risk as a monetary value, as seen in du Plessis [36] and Nel's [25] articles. Dey's [130] study on project risk used AHP and a risk matrix (risk map) to allocate a numerical value to a project's risk during project risk management.

Using Dey's study as a guideline, a risk matrix will be used to allocate a risk value associated with a specific event to determine the severity of the event that the project can prevent. The risk value will be used during the evaluation to motivate a project that will decrease the risk of an event that stops production from taking place. If a high-risk mitigation project is implemented, then the chance of an event like that moves closer to zero.

The recommendations on the risk matrix design in the mining sector are presented by Duijm [129]. Through Duijm's recommendations, a risk matrix is designed to quantify the value of the risk. Table 2-4 is an example of the risk matrix used to assess the project's risk mitigation factor.

Table 2-4: Example of the risk matrix (Developed with [129])

Risk matrix		Consequences (production loss)			
		1 < 1 day	2 1 – 2 days	3 2 days – 2 weeks	4 2 weeks – not re-open
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

Colour codes risk levels		
Level	Score	Colour
Very high	12, 16	
High	8, 9	
Medium	4, 6	
Low	1,2,3	

As shown in Table 2-4, the risk matrix will give a numerical value to the probability that something goes wrong, and the possible consequences related to production. The colour indicates the level of risk associated with the risk matrix.

In this study, the probability is considered the likelihood that if this project is not implemented, it may have severe consequences like closing the mine. The probability value is based on the condition of the haulage, system or equipment that will fail and can cause a negative impact. Should the condition be poor, the probability will be higher than if the condition is excellent. Table 2-5 shows what each row under probability means.

Table 2-5: Meaning of probability rows in risk matrix (Developed with [129])

Nr.	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 an accident can happen if the project is not implemented.
4	Certain	The probability that the event can happen is high and is a certainty.

The consequences are the number of hours, days, or weeks that the mine cannot produce ore, and it can have a significant financial impact on the mine.

Table 2-6: Meaning of consequence column in risk matrix (Developed with [129])

Nr.	Production loss time frame	Definition
1	< 1 day	Events that can happen will cause minor stoppages to the productivity of the mine, and a solution can be quickly found. The project is seen as adding redundancy to a system that is not constrained. <i>Example: One of three systems fail/trips.</i>
2	1 – 2 days	The event causes the workforce not to have access to the area to drill and blast. A lost blast is an undesirable effect if the project is not implemented. To clear up the event can take one to two days without production. <i>Example: No cooling due to leak or level fan broken.</i>
3	2 days – 2 weeks	The event causes the workforce not to have access to the area to drill and blast. To clear up the event can take two days to two weeks without production. <i>Example: FOG or unsupported area at workplace entrance.</i>
4	2 weeks – not re-open	The event causes significant damage to the infrastructure of the mine. Due to cost, access, or safety, the mine can possibly stop production indefinitely. <i>Example: Main intake or return airway (RAW) collapsing with no backup.</i>

Table 2-6 shows an example of possible consequences that can fall into each category. The risk mitigation factor of the project is an integral part of the decision-making process as it is a daily activity to lower the risk associated with mining.

2.3.2 Quantify impact

Evaluating the impact of each project happens in this phase. The impact will be best quantified using the simulation model developed in Step 1 with setting up the baseline.

The simulation model developed in Step 1 will be used as the baseline, and changes will be made to this model to represent the implementation of the projects. These changes can be, adding a fan, developing a new haulage, or adding cooling to the baseline as described in the list of projects.

When the changes to the simulation model are made, the new “what-if” simulation should portray the new underground environment conditions of the model. The results from the model should be double-checked to ensure the projects are correctly implemented and the results are acceptable.

In PTB, groups can be made of all the location data defined during the baseline. These groups with the newly configured simulation data can be exported as an Excel file to work with the data efficiently. Figure 2-10 and Figure 2-11 show the output interfaces of the AirTunnel and AirNode in PTB.

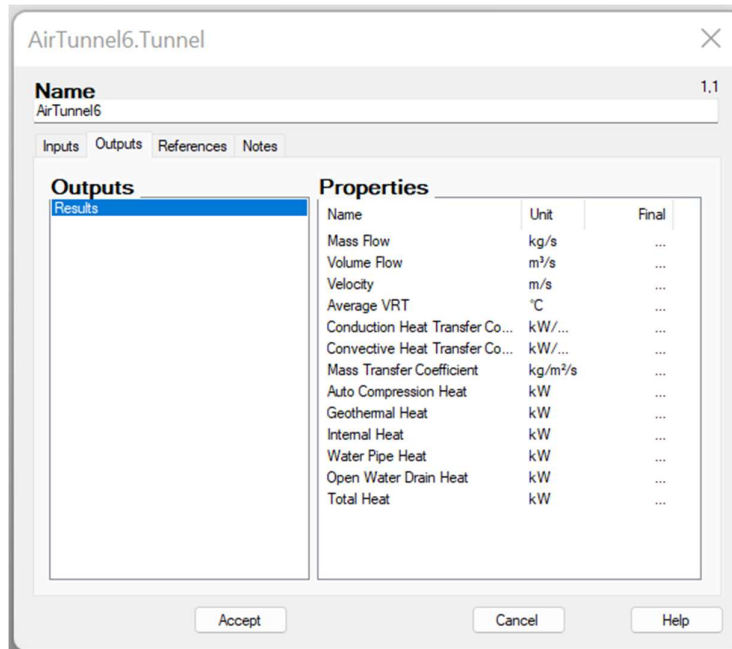


Figure 2-10: Output interface of an AirTunnel component

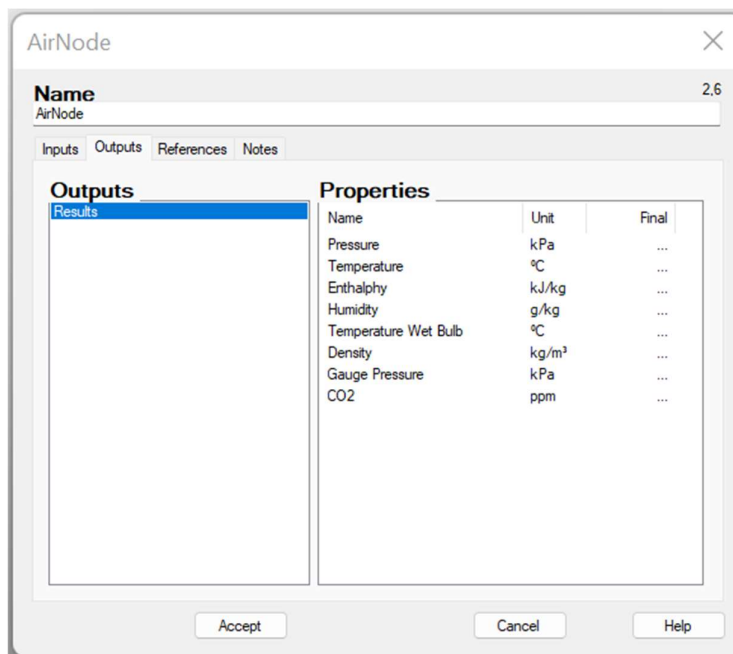


Figure 2-11: Output interface of an AirNode component

The information from these two components will be used to calculate the ACP at the identified locations in the simulation model. The ACP change will be compared with the baseline value for the entrances, and the summation of the values at the location over the whole mine will be used to express the proposed project's impact.

The implementation of these projects on the simulation model is still in the very early phase, and after the most suitable project is selected, the project's finer detail will become available. At that stage of project management, the simulation model will be developed with even more accuracy, and the project implementation should be revisited.

2.3.3 Cost analysis

An economic analysis is essential during a project selection study; during this step, the capital cost of the whole project will be estimated. The capital cost refers to the cost needed to implement the project [131]. As this is still the pre-feasibility stage, the project cost will have an accuracy of 15 to 30 % [132].

The changes made to the baseline to “implement” the project should be used to establish the project's capital cost. An approximation of the cost associated with the project can be made by historic data or quotes [132]. The costs include purchasing large equipment like refrigeration plants and machinery, developing a haulage or chamber, and rehabilitating a haulage, to name a few [23], [133]. This cost analysis during the pre-feasibility study needs to be revisited during the final project plan [107].

2.3.4 Determine energy efficiency

The energy usage of the particular project also plays a vital role in the evaluation. Many of the studies in Table 1-2 evaluated the projects based on the energy efficiency of the project [28], [31], [35], [36], [38]. Energy efficiency is part of the project's operational cost for the duration of the time and is linked to significant increases in South Africa.

The power usage function shown and discussed in Figure 2-6 will be used here to calculate the power usage of the proposed projects and compare it with the baseline. The simulations related to the power usage will be for continuous ventilating and cooling strategies to establish the worst-case scenario power usage. Should the project be selected, energy optimisation strategies can be applied.

2.3.5 Implementation time

Implementation time entails all the phases to complete the project, from initiating to commissioning. The accuracy of the implementation time will also be 15 to 30 % during the project feasibility phase and will improve as more detailed planning is done [132].

All the information is now collected from the project evaluation step of this method. The next step of this method is to use the MCDM method to select the best project.

2.4 Step 3: Formulate evaluation criteria

Step 3 of the method is formulating the evaluation criteria weights, which entails using an MCDM method to determine the importance of the criteria used to evaluate the decision-making problem. Figure 2-12 shows the sub-steps in Step 3 of ranking environmental improvement projects.

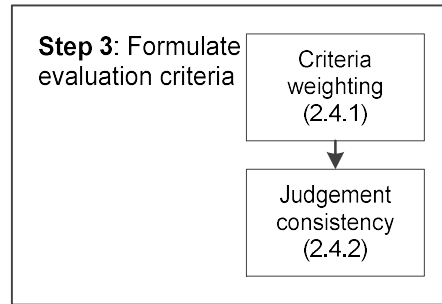


Figure 2-12: Two phases of Step 3 of the method

In Figure 2-12, the first phase uses the AHP method to estimate the priorities of the criteria, weighting the criteria, while the second phase checks the consistency of the weighting process.

The AHP is selected as the MCDM because it takes the complex, multi-attribute problem and hierarchically structures it to solve an MCDM choice problem [134]. Another advantage is that the AHP is easy-to-use with the function to detect inconsistent judgement through consistency control. The main objective of the AHP in this project evaluation method, is to identify the relative weights of the criteria, considering their impact on the decision-making process. The relative weights will be determined by using the pairwise comparison scale. Figure 2-13 is the schematic illustration of the AHP method used for this decision-making problem.

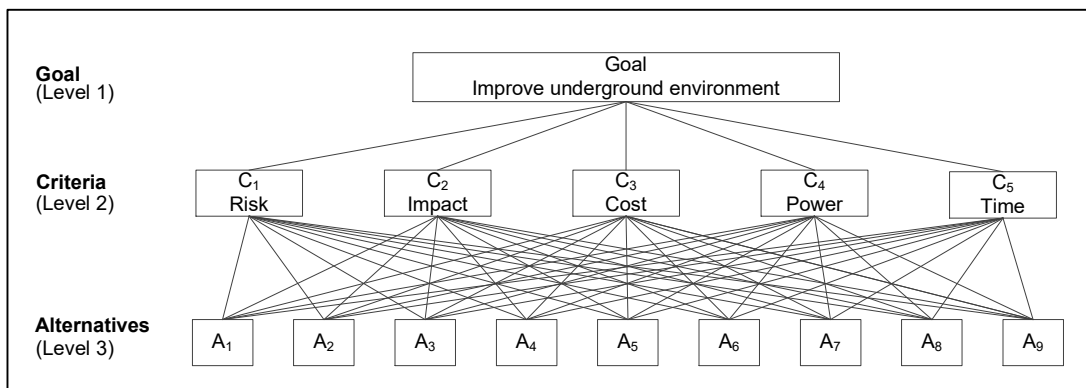


Figure 2-13: Schematic framework of the AHP method

The first level in Figure 2-13 is the goal of the decision-making process which is to select the most suitable project to improve the underground environmental conditions. The second level is the criteria that were decided on in Step 2. Table 2-7 shows the criteria with the symbols used in AHP.

Table 2-7: Evaluation criteria

Symbol	Criteria	Measurement	Goal (attribute)
C ₁	Risk	Qualitative (subjective)	Max
C ₂	Impact	Quantitative (objective)	Max
C ₃	Cost	Quantitative (objective)	Min
C ₄	Power	Quantitative (objective)	Min
C ₅	Time	Quantitative (objective)	Min

The order of the criteria is essential as this will be used during the criteria weighting to establish the importance of the higher-order criteria to the lower-order criteria. The order of these criteria is derived from the literature.

Order of criteria

The risk associated with significant events can obstruct the whole goal of the mining company and make it fail and that is why risk is the most important factor [122]. The goal is to improve the underground environment, so the impact criteria should be second. The cost and power are third and fourth since, in evaluation studies, they are equally weighted, and power is a part of the operational cost of the projects [34], [38]. Time is part of the iron triangle of project management and is added at the end to see if the project will be viable [135]. This order will establish the criteria weight during the next phase.

The third level in Figure 2-13 is the projects that will be evaluated using the criteria. The projects will be indicated with an *A* during the MCDM process. The first phase of this step will be used to weigh these criteria.

2.4.1 Criteria weighting

The criteria should be weighted according to the essential aspect of the decision-making process. In the case of this method, it is to improve the underground thermal conditions. The subjective judgement of the decision-makers will be quantified using a pairwise comparison, which will give a magnitude to each criterion [136]. Table 2-8 shows the pairwise comparison scale.

Table 2-8: Measurement's scale of pairwise comparison [136]

Verbal judgement or preference	Numerical rating	Definition
Equally important	1	Two requirements (<i>i</i> and <i>j</i>) of equal value.
Moderately important	3	Experience slightly favours one (<i>i</i>) requirement over another (<i>j</i>).
Strongly important	5	Experience strongly favours one (<i>i</i>) requirement over another (<i>j</i>).
Very strongly important	7	A requirement (<i>i</i>) is strongly favoured, and its dominance is demonstrated in practice.
Extremely important	9	Evidence favouring one (<i>i</i>) over another (<i>j</i>) is of the highest possible order of affirmation.
Intermediate	2, 4, 6, and 8	Median values between two definitions.

The numerical value obtained from Table 2-8 will be used to construct a pairwise comparison matrix, also called a judgement matrix. The pairwise comparison values are used within the judgement matrix to establish the importance of the higher-order criteria to the lower-order number, as ranked in Table 2-7. The only point in the method where the decision maker's preference can influence the decision, is during this phase of Step 3, however; it is limited since the order of the criteria is specified.

The judgement matrix is a square matrix of the order n [52]. The n refers to the number of criteria that needs to be weighted. This method will have n of five. Equation 2-3 is the construction of a judgement matrix.

Equation 2-3: Judgement matrix [52]

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

The judgement matrix in Equation 2-3 is used to allocate the relative importance, a_{ij} , of the criteria, C_i , with respect to criteria C_j is expressed as A , where the following is true:

$$a_{ij} = 1 \text{ when } i = j \quad \text{and} \quad a_{ij} = \frac{1}{a_{ji}} \text{ when } i \neq j$$

The next step is to normalise the judgement matrix and calculate the priorities of each matrix. Equation 2-4 is used to normalise the judgement matrix.

Equation 2-4: Normalised the judgement matrix [74]

$$\bar{A}_{ij} = \frac{A_{ij}}{\sqrt{\sum_{i=1}^n A_{ij}^2}}$$

In Equation 2-4, the judgement matrix's column values are summed, and each element is divided by the respective column's total value. Equation 2-5 is then used to calculate the relative weights.

Equation 2-5: Calculate the relative weights

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

Where:

$\bar{a}_{ij}$ = Normalised element

Calculating the row's average, the relative weights of each criterion are obtained. Thus $W = [w_1 \ w_2 \ \dots \ w_n]$ is the criteria weight vector with the mathematical condition in Equation 2-6.

Equation 2-6: Mathematical condition [137]

$$\sum_{i=1}^n w_i = 1$$

Where:

w = Criteria weight

As the criteria are weighted, the next phase is to perform a consistency control.

2.4.2 Judgement consistency

The judgement consistency (consistency control) ensures that the judgement matrix is acceptable and reasonable [138]. An error in judgement is acceptable when the consistency ratio (CR) is smaller than 10% [139]. The following should be used to calculate the consistency ratio:

Firstly, identify the consistency vector, CV . Use Equation 2-7 to calculate the consistency vector.

Equation 2-7: Calculate consistency vector, CV

$$[CV] = [A] \cdot [W] = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{21} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} cv_1 \\ cv_2 \\ cv_3 \\ \vdots \\ cv_n \end{bmatrix}$$

In Equation 2-7, the judgement matrix $[A]$ and criteria weight vector $[W]$ is multiplied. The eigenvalue (λ_i) of each criterion in the consistency vector is calculated using Equation 2-8.

Equation 2-8: Calculate eigenvalue [139]

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

Where:

λ_i = Eigenvalue

cv_i = Consistency element

Equation 2-8 the eigenvalue is calculated by dividing the weighted sum (cv_i) of the column by criteria weight (w). Relative weights represent the principal eigenvalues of each criterion, with the highest eigenvalue given by λ_{max} [96]. Equation 2-9 is used to calculate the λ_{max} .

Equation 2-9: Calculate the highest eigenvalue [96]

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

When the λ_{max} is calculated, the consistency index can be calculated using Equation 2-10.

Equation 2-10: Consistency index (CI) [140]

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

After the CI is calculated, the consistency ratio needs to be calculated. Equation 2-11 is then used to compute the consistency ratio.

Equation 2-11: Consistency ratio (CR) [140]

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

Where:

RI = Average random index value.

The average random index value is obtained using the judgement matrix's order, and with the order of the matrix of five, the RI value is 1.12. When the consistency ratio is larger than 10%, the criteria weighting process needs to be redone [73]. At the end of Step 3, the decision-maker should have a decision matrix with the criteria weighted. Equation 2-12 is the decision matrix.

Equation 2-12: Decision matrix [96]

$$R = \begin{matrix} & \begin{matrix} \text{Risk} & \text{Impact} & \text{Cost} & \text{Power} & \text{Time} \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_n \end{matrix} & \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ x_{21} & x_{22} & x_{23} & x_{24} & x_{25} \\ x_{31} & x_{32} & x_{33} & x_{34} & x_{35} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & x_{n3} & x_{n4} & x_{n5} \end{bmatrix} \end{matrix}$$

The next step will be to rank the projects.

2.5 Step 4: Optimise project selection

The MCDM method used to optimise the project selection is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method.

The TOPSIS method was selected to rank the project based on the rationale and transparency of the MCDM method [141]. The TOPSIS also have the advantage, above the other MCDM methods, of calculating the best project the quickest [142]. The user-friendliness and high simplicity of the TOPSIS method improve the interaction of the method by decision-makers and shareholders that do not have a technical background [76].

The TOPSIS method is practical and ranks the projects from the most suitable to the least suitable for improvement [46], [76]. The TOPSIS methodology to select the most suitable project is visually illustrated in Figure 2-14.

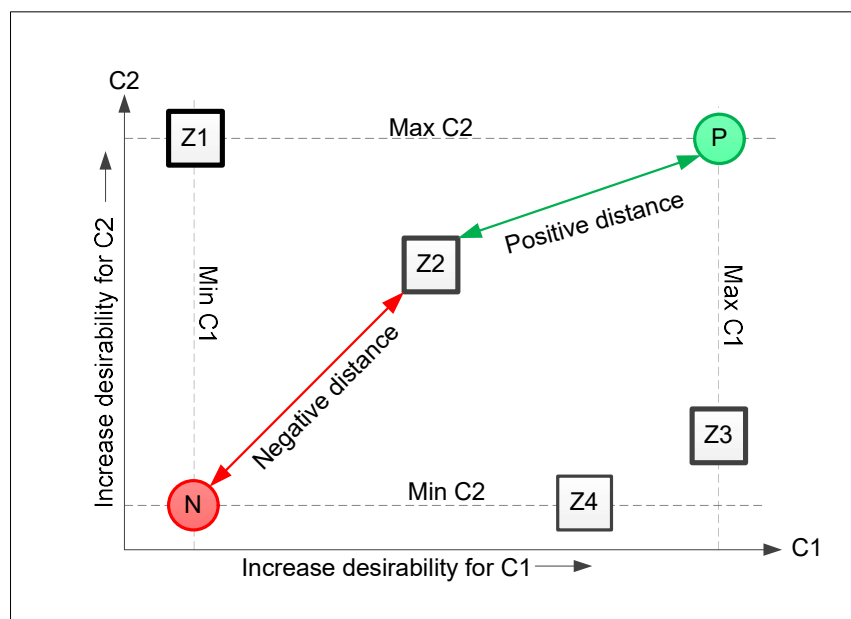


Figure 2-14: Visual presentation of the TOPSIS method

The squares in Figure 2-14 present the selected projects; the circle with the P presents the positive ideal solution (ideal solution), and the circle with the N presents the negative ideal solution (non-ideal solution). The green arrow indicates the geometric distance of Z2 to the ideal solution, and the red arrow shows the geometric distance to the non-ideal solution. Through this, the TOPSIS method calculates which project is the most suitable. The TOPSIS method concept is to select the most suitable project with the shortest distance, in a geometrical sense, to the ideal solution [101]. This is only a two-criteria illustration, but the same principle is applied to more criteria.

Figure 2-15 shows the phases in Step 4 of the ranking of environmental improvement projects.

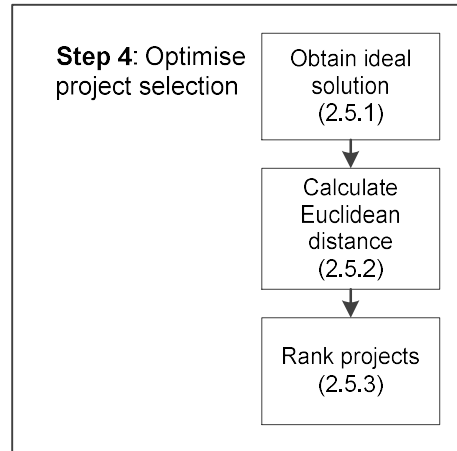


Figure 2-15: Three phases of Step 4 of the method

In Figure 2-15, the first phase obtains the ideal solutions, the second phase calculates the Euclidean distance, and the last phase ranks the projects.

2.5.1 Obtain ideal solution

The weighted normalised decision matrix should be calculated to obtain the negative and positive ideal solutions [74]. Equation 2-4 can be used to calculate the normalised matrix of the decision matrix (R). The normalised decision matrix should then be multiplied by the weights criteria. The weighted normalised decision matrix is obtained using Equation 2-13.

Equation 2-13: Weighted normalised matrix [74]

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

The weighted normalised vector is represented as V_{ij} and v_{ij} represent the elements.

2.5.2 Calculate Euclidean distance

The Euclidean distance is the geometrical distance of each project to the ideal solution [137]. First, the range of each matrix's column should be determined; this depends on the attributes of the criteria. A higher or lower value is favoured, for example, a maximum value for impact and risk while a minimum value for cost, power, and time. In Table 2-7, the maximum and minimum attributes of the criteria are listed in the fourth column.

Using the weighted normalised decision matrix, the best performance scores make the positive ideal solution (PIS), while all the worst performance scores make the negative ideal solution (NIS) [87]. Using Equation 2-14 and Equation 2-15, the ideal solution is calculated.

Equation 2-14: Positive ideal solution [87]

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

In Equation 2-14, the highest value of that column must be added to the V^* list for the maximum attributes while the lowest value for the minimum attribute.

Equation 2-15: Negative ideal solution [87]

$$V^- = \{v_{-1}^-, v_{-2}^-, \dots, v_{-n}^-\} = \{(min_j v_{ij} | i \in I'), (max_j v_{ij} | i \in I'')\}$$

Equation 2-15, the smallest value for the maximum attributes and the highest value for the minimum attribute must be added to the V^- list.

The list of the PIS (V^*) and the NIS (V^-) will be used in the next step to determine the distance from the ideal solution [65]. Equation 2-16 and Equation 2-17 are used to determine Euclidean distance.

Equation 2-16: Project's distance from PIS [65]

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

In Equation 2-16, each project's criteria values' distance to the positive ideal solution, identified in Equation 2-14, is calculated.

Equation 2-17: Project's distance from NIS [65]

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

The same is done with Equation 2-15 and Equation 2-17 for the negative ideal solution. The project's distance is now calculated for each row.

2.5.3 Rank projects

The relative closeness to the ideal solution is used to rank each project. Equation 2-18 is used to calculate the relative closeness.

Equation 2-18: Relative closeness [74]

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

Using the values calculated by Equation 2-18, the projects can be ranked in decreasing order.

2.6 Verification of method

The definition of verification:

Verification refers to if the method developed in this section addresses the objectives of this study identified in Section 1.8.²

The objectives in Section 1.8 will be compared to the method to establish how the method in Chapter 2 addresses the study's needs. Table 2-9 shows how the proposed method addresses the objectives of this study.

Table 2-9: Verification of the proposed method

Objective	Addressed in method
Develop a method to evaluate (1) and rank (2) various improvement projects	(1) Step 1 of the method sets up the evaluation environment through the information and model development, where Step 2 evaluates all the projects. (2) Steps 3 and 4 use MCDM methods to rank the projects based on suitability.
Incorporate MCDM methods to rank projects	MCDM methods, AHP and TOPSIS, were incorporated in Steps 3 and 4, respectively.
Integrate simulations with MCDM methods	During the evaluation of the projects, the second phase of Step 2 integrates ventilation simulations to determine the impact of the projects on the holistic underground ventilation and cooling system. The impact will be used as an input to the MCDM methods.

Table 2-9 shows that all objectives are addressed through the developed method.

The method in Chapter 2 was constituted by consulting various research studies to develop a method that will be used to satisfy the need for the study identified in Chapter 1. Step 1 combines different literature to establish the environment for project evaluation to improve the underground

² Definition from North-West University's masters marking paper

environment. The motive for the criteria in Step 2 was based on publications highlighting the necessary criteria during the decision-making process. The AHP method used in Step 3 to weigh the criteria is an existing method that was verified during numerous studies in the past, even in the mining sector. The TOPSIS method used in Step 4 was also previously used in different case studies.

2.7 Conclusion

This Chapter elaborated on the method developed to evaluate and rank environment improvement projects. The first two steps were used to evaluate the projects and collect all the information to assist in the decision-making process. In the third and fourth steps, a hybrid combination of the MCDM methods was used to assist during the decision-making process to rank the projects. Figure 2-16 illustrates the complete method.

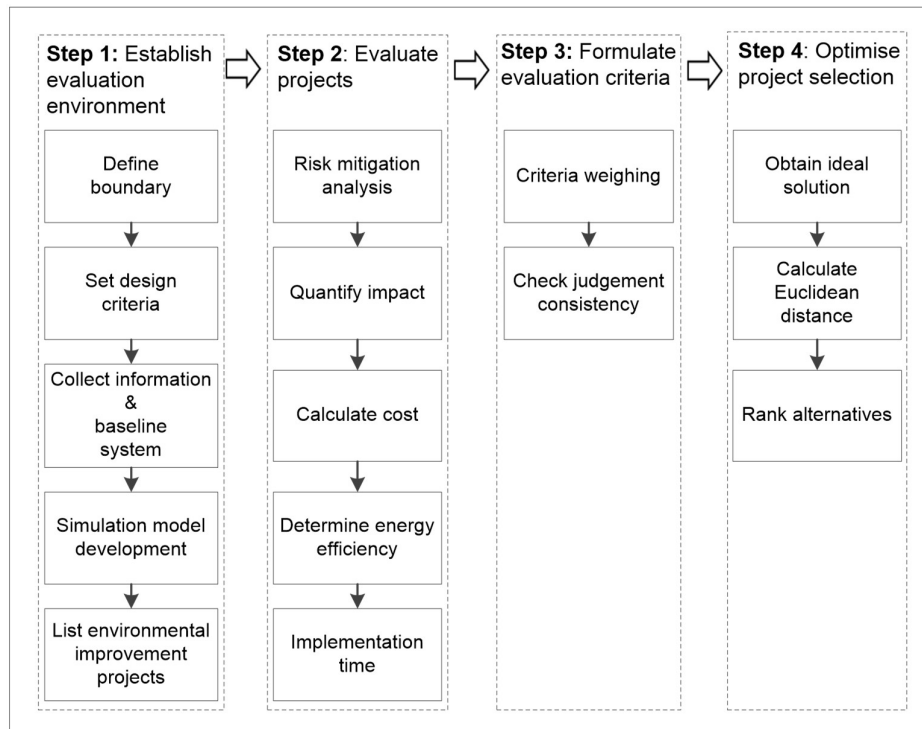


Figure 2-16: Complete method to evaluate and rank projects

3. APPLICATIONS AND RESULTS

3.1 Preamble

This Chapter entails using the method developed in Chapter 2 and applying it to a real-world case study. The implementation of the case study validates the method. The latter part of this chapter will focus on implementing the method in a case study before concluding.

3.2 Case study mine

3.2.1 Background

The mine is a gold mine situated on the outskirts of Welkom in the Free State province of South Africa. The average production rate of the mine is 55 000 tonnes of ore per month. Figure 3-1 is a top view of the mining complex.

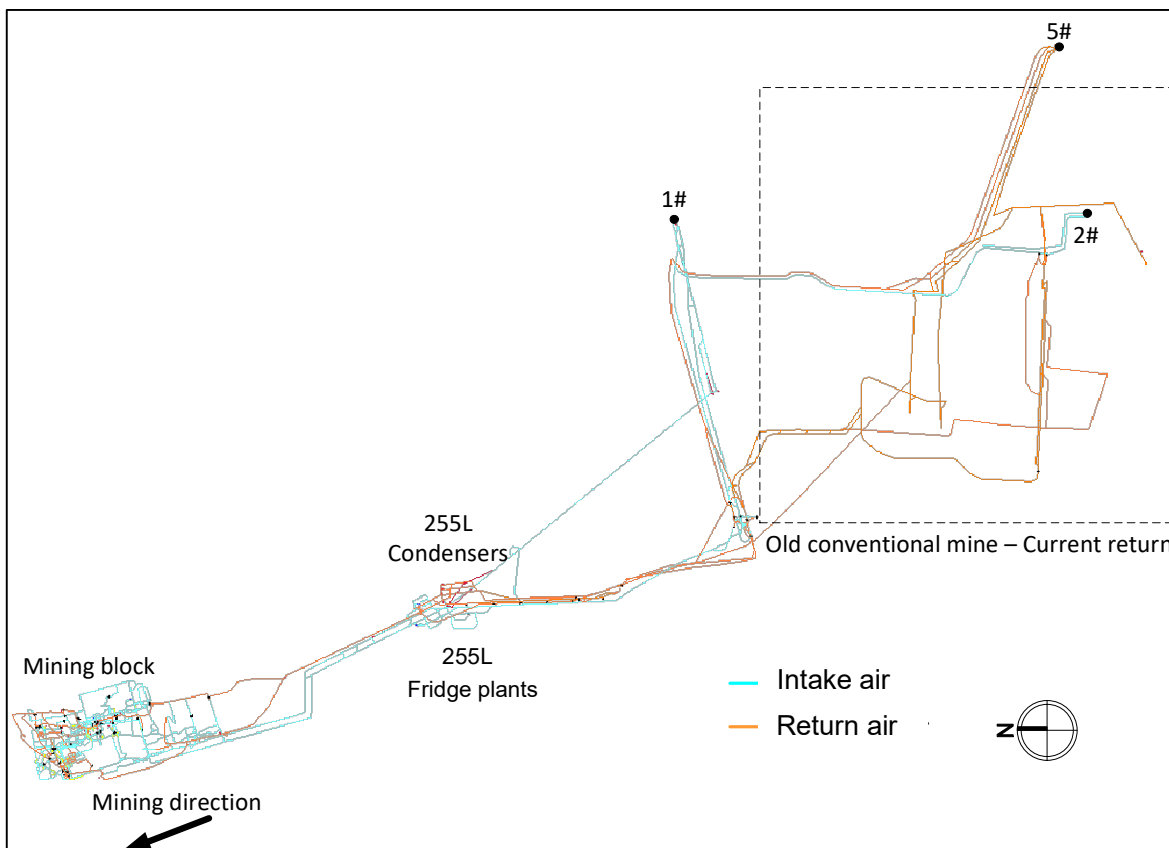


Figure 3-1: Top view of the mining complex

As illustrated in Figure 3-1, the mine consists of two downcast shafts (1# and 2# in Figure 3-1) and one return shaft (5# in Figure 3-1). The upper part of the mine's old, depleted areas is used as the

return airway for the mine. Mining takes place in the mining block (MB) situated 6 km from the main shaft, while conveyor belts transfer ore and mine employees from the shaft to the work areas.

The mining methods combine narrow reef and massive open stope mining. The upper part of the MB uses conventional narrow reef mining with high-grade gold and serves as de-stressing for the massive mining. The lower part of the mining block uses trackless diesel machinery to mine the massive orebody.

The mixture of gold deposits and mining methods makes managing the ventilation and cooling system difficult. There are extensive ventilation and cooling inefficiencies in the mine, with some infrastructure from the cooling hierarchy in Figure 1-5, not installed. The inefficiencies are due to cost-cutting measures, incorrect planning, and substandard maintenance.

As the mine is in a difficult situation to keep the underground environment to acceptable working standards, the management investigated large capital projects that can be implemented to improve the underground thermal environment. This study's method will be implemented at this mine to improve the underground environment.

3.2.2 Step 1: Establish evaluation environment

Step 1 is to collect the information, develop the simulation model and form a list of various projects that can be used to improve the mine's underground environmental conditions. Step 1's phases are highlighted in blue in Figure 3-2.

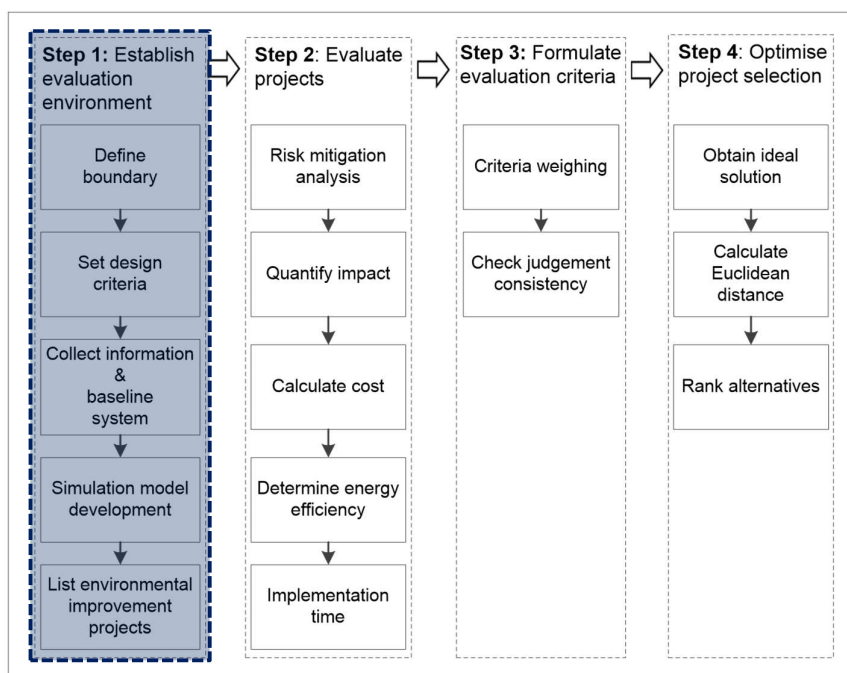


Figure 3-2: Step 1 of the methodology – Establish evaluation environment

Define boundary

The MB and the airways supplying the mine with air need to be included in the boundary. Figure 3-3 illustrates the boundary of the mine.

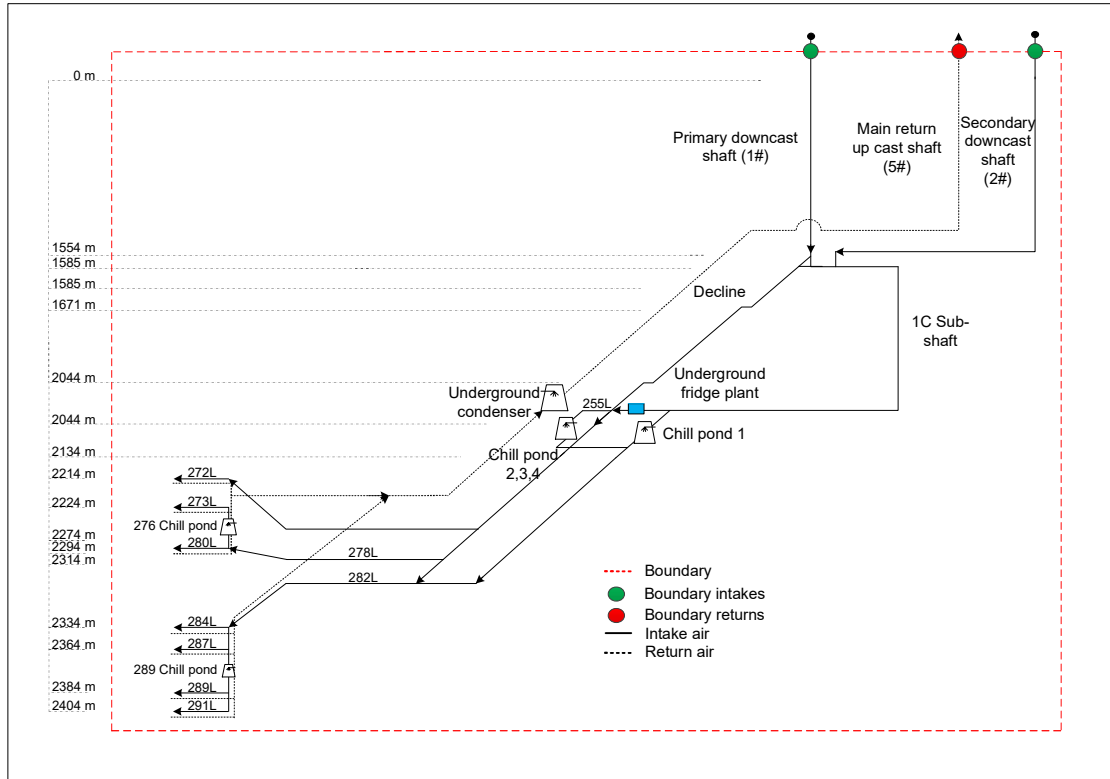


Figure 3-3: The mine's boundary

The red dotted line in Figure 3-3 shows the boundary that includes the three shafts which make up the mine. The boundary includes the 1C-sub shaft, underground refrigeration circuit and the complete mining block.

Set design criteria

The mining company sets the design criteria to ensure the underground temperatures stay below the legal requirements set by the DMRE and to create a favourable working environment for the workforce.

Table 1-1 in Section 1.2.1 shows the legal temperature requirements as stated by the DMRE. To achieve favourable working conditions, the company specified a wet-bulb temperature of 26.5°C at the entrances of the levels with a velocity of 0.75 m/s. Using

Equation 2-1, the ACP was calculated to be 296.6 W/m². A design ACP value of 300 W/m² will be used during these calculations.

The design criteria are now set; next, all the information can be collected to set the baseline.

Collect information & baseline system

(i) Collect information

The information is obtained in different formats, such as Figure 3-4, which shows an example of a DXF file collected from the planning department.

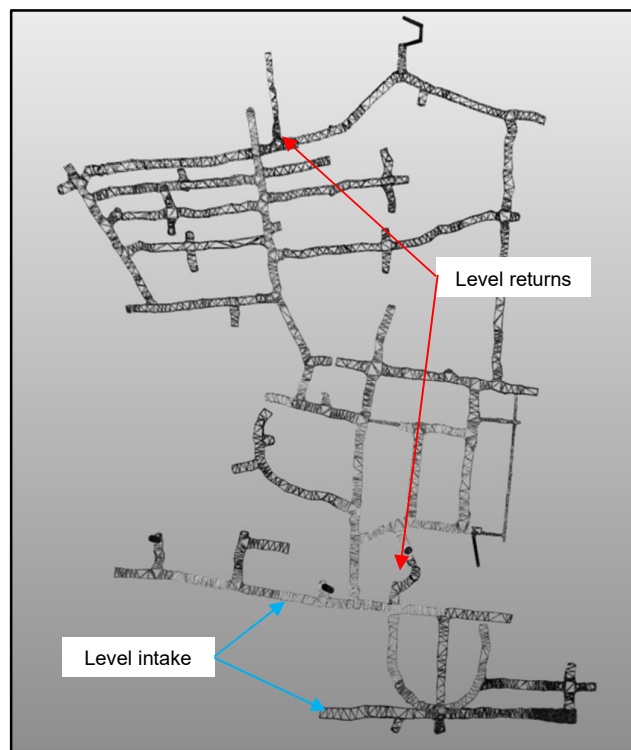


Figure 3-4: DXF of Level 291

The DXF contains the depth and gradient of the haulages, haulage sizes, and future development. The other information formats are supplied by the ventilation department and include the airflow plans. Figure 3-5 is an example of the airflow plan for Level 291.

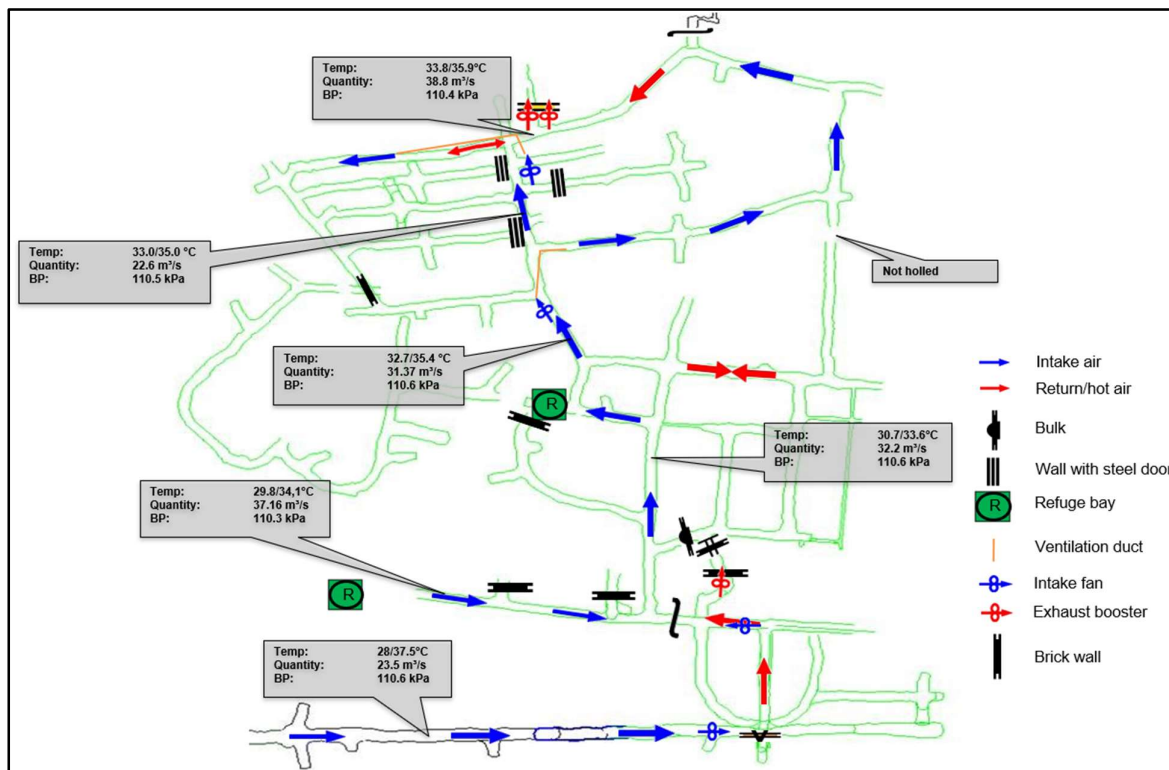


Figure 3-5: Airflow plan for Level 291

The airflow plan in Figure 3-5 shows the direction of the air, all the ventilation equipment that can influence the airflow and the measurements taken during a ventilation audit. The ventilation audit information graphs indicated in grey blocks in Figure 3-5, show the locations' temperature, quantity, and barometric pressure. The mine selects the audits' locations, which give an overall picture of the airflow through that level.

Cooling information for the mine can be collected through their reporting system linked to the mine's SCADA system and the historical database. Figure 3-6 shows the two cooling circuits with their pipe connections.

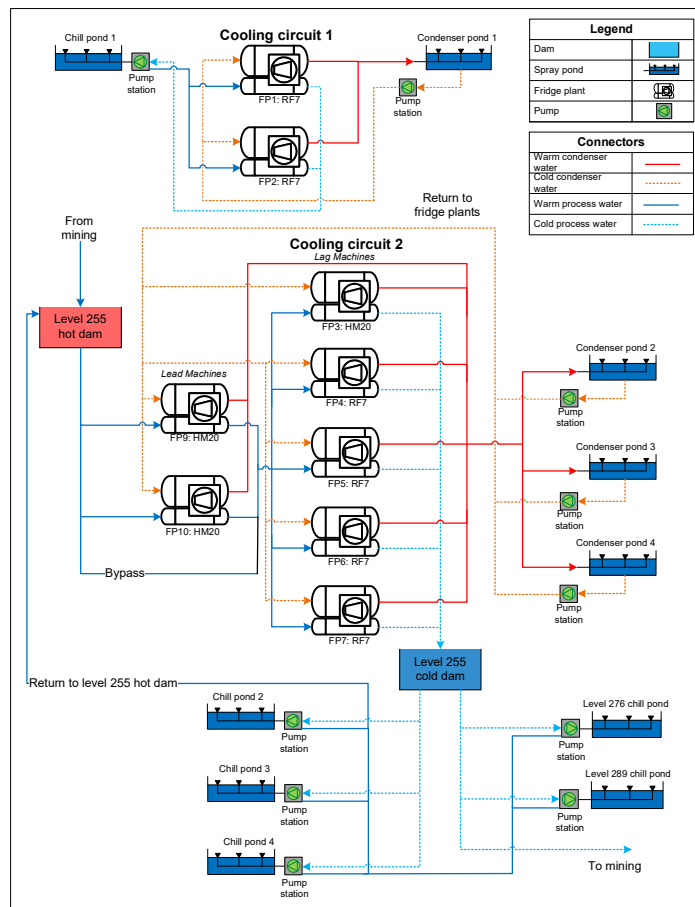


Figure 3-6: Mine's refrigeration circuit layout

Figure 3-6 shows that the refrigeration circuit is split into two circuits: dedicated refrigeration plants, condenser ponds and bulk air coolers. Cooling circuit 1 (CC1) has two refrigeration plants, while cooling circuit 2 (CC2) has seven refrigeration plants. CC1 has one dedicated condenser pond and a chill pond. CC2 has three condenser ponds, a cold dam that supplies three chill ponds on Level 255, two chill ponds in the mining block and chilled water for mining activities. Two kinds of refrigeration plants are used, namely HM20s and RF7s. Figure 3-7 shows an example of the daily reporting system used by the mine.

Fridge plant (FP)	Utilisation (%)	GV Pos (%)	Duty (kW)	Duty target (kW)	Evaporator inlet T (°C)	Evaporator ΔT (°C)	Evaporator flow (l/s)	Condenser inlet T (°C)	Condenser ΔT (°C)	Condenser flow (l/s)	COP
FP1	100.0	95.3	1 645	2 270	15.9	6.5	60.0	41.0	3.0	154.8	2.5
FP2	0.0	-	-	-	-	-	-	-	-	-	-
FP3	100.0	99.3	5 775	4 100	16.3	9.6	144.1	43.6	10.1	146.0	3.6
FP4	100.0	99.4	1 600	2 270	15.2	6.1	62.4	42.0	4.6	113.3	2.3
FP5	100.0	99.7	1 606	2 270	16.3	6.7	57.2	42.0	5.9	91.1	2.5
FP6	0.0	-	-	-	-	-	-	-	-	-	-
FP7	0.0	-	-	-	-	-	-	-	-	-	-
FP9	0.0	-	-	-	-	-	-	-	-	-	-
FP10	100.0	73.8	4 343	4 100	20.9	6.2	166.3	41.4	7.5	194.9	2.6

Figure 3-7: Cooling infrastructure information - Daily reporting

The cooling infrastructure can be collected from the mine's SCADA system and historical database to set the baseline.

(ii) Baseline system

The red letters in Figure 3-8 indicate the entrance to the levels from where the projects will be evaluated.

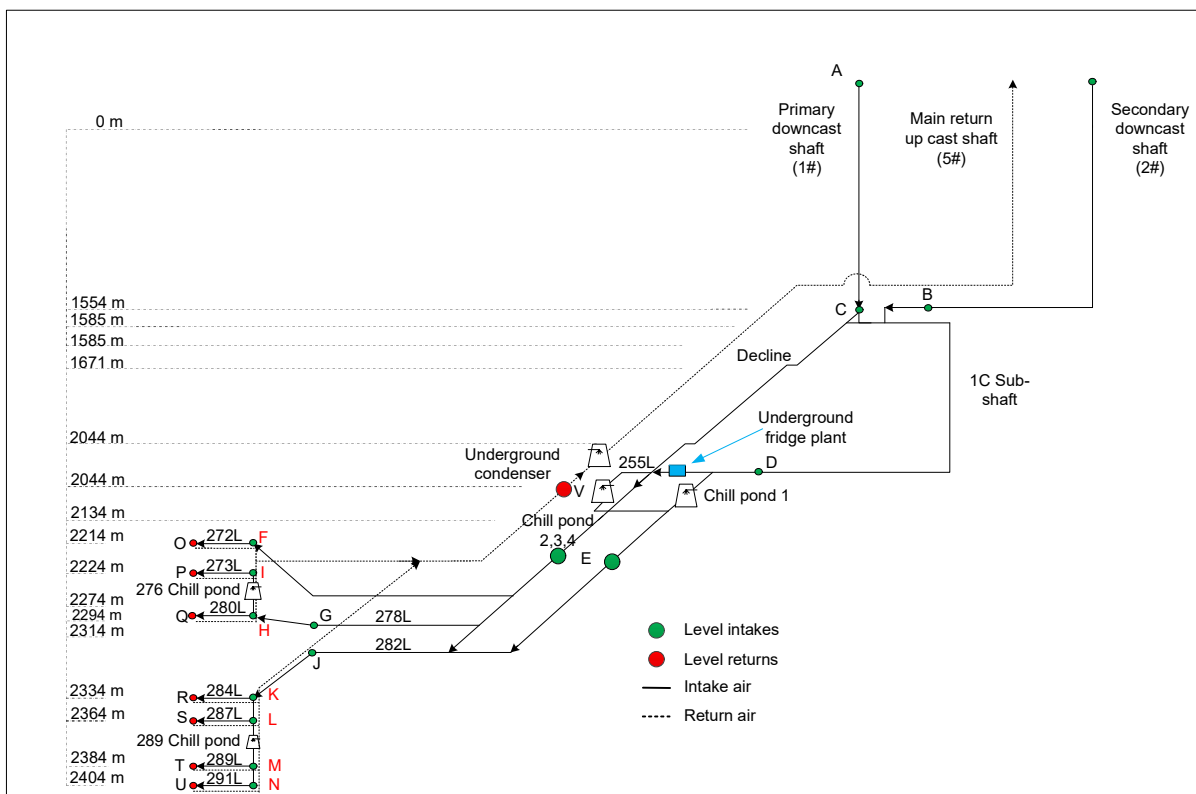


Figure 3-8: Schematic of the intakes and returns of the mine

The airflows and temperatures for the locations illustrated in Figure 3-8 are shown in Table 3-1. The red letters indicate the selected points used during the project evaluation. The reference A to N refers to the locations in Figure 3-8.

Table 3-1: The mine's intake flows and temperatures

Ref.	Level	Intake				
		Mass flow (kg/s)	Velocity (m/s)	Wet-bulb Temp (°C)	Dry-bulb Temp (°C)	ACP (W/m ²)
A	Surface	236.8	5.4	20.0	28.0	1283.8
B	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#)	56.5	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

The return temperatures used in calibrating the simulation model are shown in Appendix A: Return temperatures. The information collected from the daily reporting, as shown in Figure 3-7, will be used to baseline the underground refrigeration circuit on 255 level. The refrigeration circuit supplies chilled water, as drilling and cooling water, to the mining block. The refrigeration circuit's cooling duty is 10 129 kW and comprises nine refrigeration plants. Table 3-2 shows the cooling infrastructure baseline.

Table 3-2: The mine's cooling infrastructure

Refrigeration circuits					
CC1		CC2 (Lead machines)		CC2 (Lag machines)	
Fridge Plants	Duty (kW)	Fridge Plants	Duty (kW)	Fridge Plants	Duty (kW)
FP 1	1 654	FP9	4 964	FP3	4 522
FP 2	2 606	FP10	2 605	FP4	1 751
-	-	-	-	FP5	1 884
-	-	-	-	FP6	2 248
-	-	-	-	FP7	2 053
Current cooling duty (kW)			10 129		
Plants running			FP 2 (CC1)		
			FP 10 (CC2 Lead machines)		
			FP 3, 5, 6 (CC2 Lag machines)		
Plant utilisation (Average %)			73		
Cold dam temperature (°C)			15		
Average MB water usage (ℓ/s)			110		
Chill ponds					
Chill pond		Water flow (ℓ/s)		Duty (kW)	
Chill pond 1 (CC1)		50		1 360	
Chill pond 2 (CC2)		50		1 239	
Chill pond 3 (CC2)		50		2 193	
Chill pond 4 (CC2)		50		2 103	
276 L Chill pond (MB)		25		604	
276 L Chill pond (MB)		25		977	

* Average data collected over one year

The following section will use the ventilation and cooling information collected to develop the simulation model.

Simulation model development

Step A from the flow diagram in Figure 2-7 is to import the DXF layouts, shown in Figure 3-4. The DXFs forms the model's skeleton, which is used as a guide for the network to be built. Figure 3-9 shows the full mine DXF in PTB.

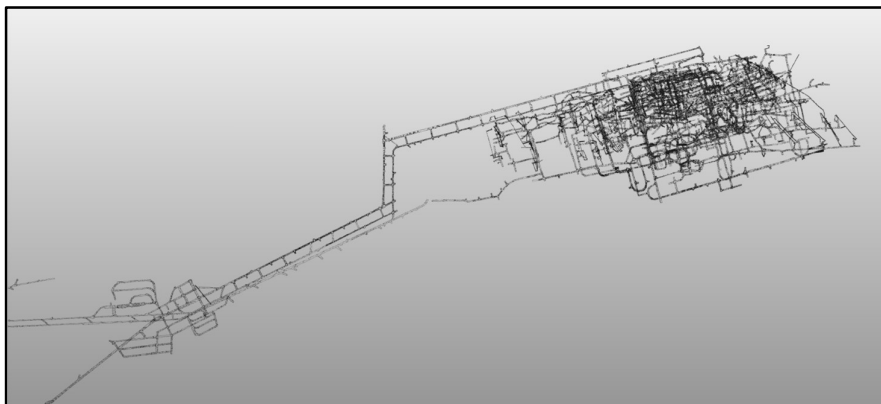


Figure 3-9: DXF model of the mine in PTB

Step B of Figure 2-7 inserts the collected and measured data and the ventilation haulages, fans and refrigeration circuits can now be built per level according to the DXF and airflow layouts. The ventilation haulages are represented by AirTunnels and AirNodes and can be seen in Figure 3-10.

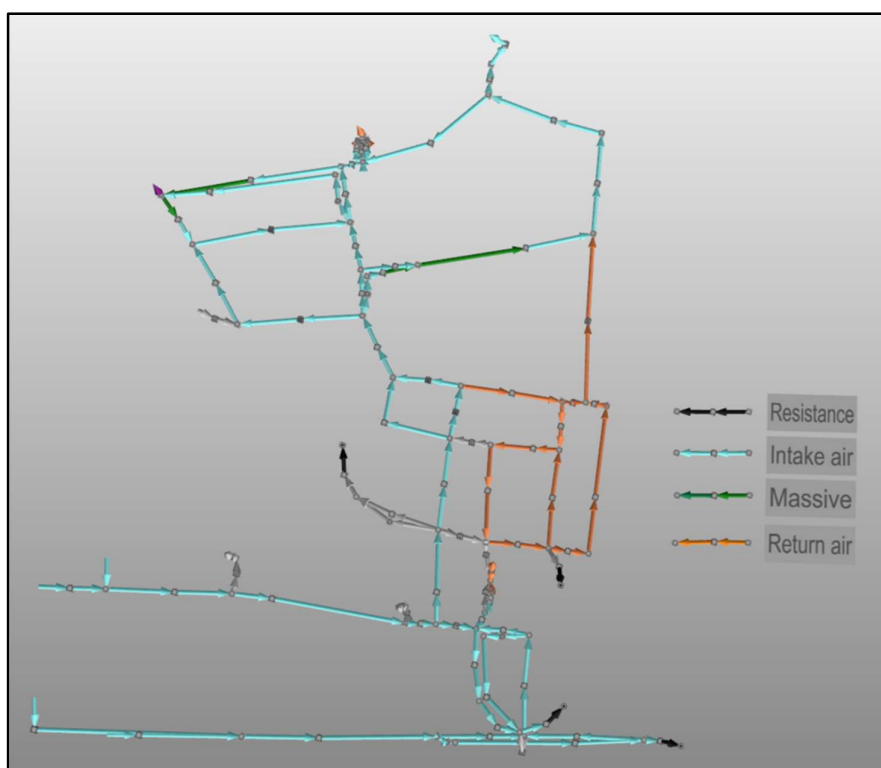


Figure 3-10: Ventilation network of tunnels and nodes in PTB for Level 291

The same is done for the refrigeration circuit, where the layout in Figure 3-6 is built into the PTB software. Figure 3-11 shows the refrigeration circuit built in PTB.

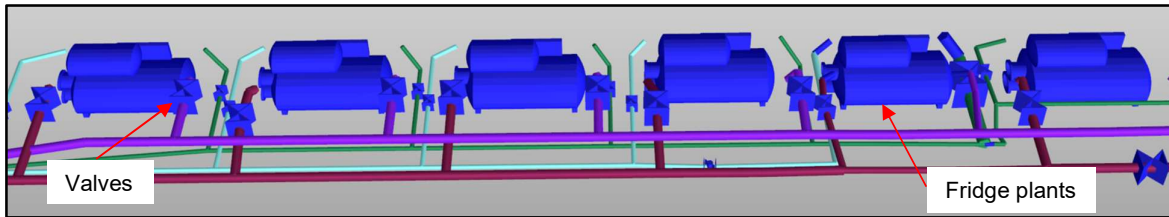


Figure 3-11: Cooling infrastructure, refrigeration plants in PTB

Step C of Figure 2-7 simulate the model and establish how the developed model duplicates the underground environment. During Step D, the results should be compared with the measured data. The results were not satisfactory after the first iteration, and steps C, D and E were iterated eight times for the model to reach the acceptable accuracy.

The percentage error was calculated using Equation 2-2 for all the locations shown in Figure 3-8. It was separately calculated for the mass flow, wet-and dry-bulb temperatures. These values are shown in Appendix B: Determine model accuracy. The model's average percentage error was 4.8%, with an airflow error of 8.7%, a wet-bulb temperature error of 3.9% and a dry-bulb temperature of 1.9%. Figure 3-12 shows each level's average percentage error per level and the overall error percentage.

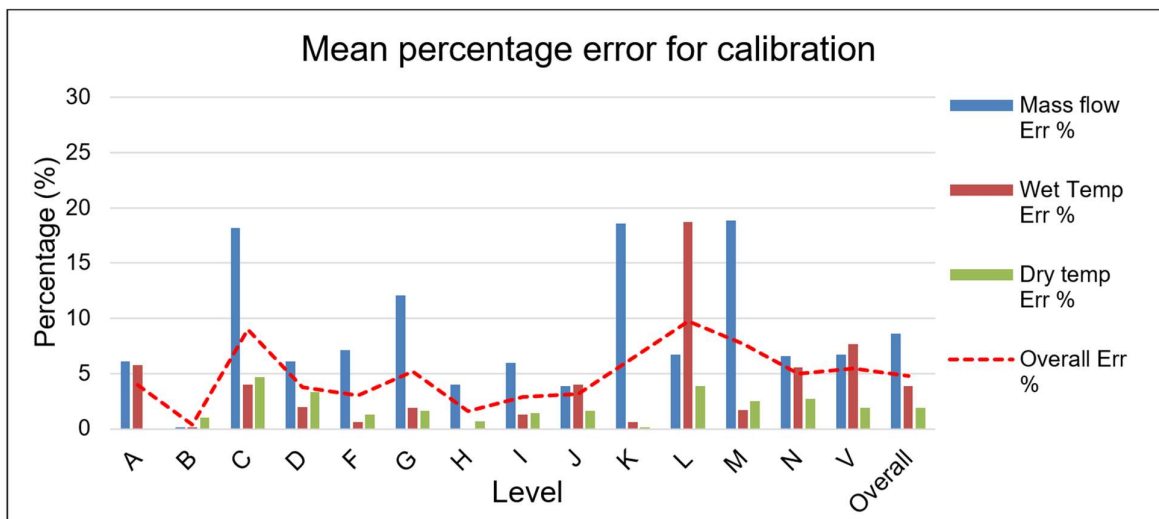


Figure 3-12: Percentage error on the model calibration

The model achieved an accuracy of 95.2%, rendering an accurate representation of the underground environment, acceptable for the next step. Figure 3-12 shows that the upper mining block is better calibrated than the lower mining block. The reason is that the error from the top mining block propagates to the lower mining block because of the mine's interconnectivity.

The simulation model is now developed and can simulate different projects to improve the underground environment.

List environmental improvement projects

The engineers and occupational hygienists used their experience with Table 2-2 and Table 2-3 as a guideline to create a list of possible projects that can improve the underground environment. The design criteria present both the ventilation and cooling environment, but the projects will be divided into separate sub-sections.

(i) Ventilation

Table 3-3 presents a list of the different projects to improve the ventilation underground and a description of the project's assistance in this task.

Table 3-3: Proposed projects to rectify the airflow quantity

Symbol	Project	Description	Reason
A ₁	Additional/ new shaft	Develop a new shaft (intake and return) from the surface to the mining block.	This will entail a shorter travel distance for the air while not using the current old intake and returning airways.
A ₂	Cross-over	Develop a cross-over to link two haulages on 52 level.	Increase the RAW area from one haulage to two haulages. Increase return capacity on 52 level.
A ₃	Condenser 5	Develop a new condenser pond and add a booster fan.	Increase the heat exchange capabilities of the cooling circuit on 255 level and increase the return capacity by adding an additional fan.
A ₄	Additional fans in the RAW	Place two fans in the east and west RAW and regulate the flow to each level of the mining block.	This will place the mining block under positive pressure. Decrease the leaks into the mining block.
A ₅	New straight RAW to 1#	Develop a return haulage from the back of the condenser ponds to 1#.	A shorter distance will help decrease dependence on the old return system and the return resistance.
A ₆	Rehabilitate the current RAW	Re-establish the RAW between 1# and 5# to its original condition.	Increase reliability through re-supporting and decrease the resistance by removing FOG.
A ₇	Additional RAW to 5#	Develop a twin RAW from 63 L to 52 L at 5#.	Increase the RAW capacity and lower the return resistance.
A ₈	Additional intake and return haulage	Develop an additional mining block intake and return haulage.	Increase the intake and return volume capabilities.

The eight projects listed in Table 3-3 will be further evaluated in Step 2 with the proposed cooling projects developed below.

(ii) Cooling

Table 3-4 features proposed projects to improve the cooling underground and a description of the project assistance in this task.

Table 3-4: Proposed projects to rectify the cooling shortfall

Symbol	Project	Description	Reason
A ₉	Underground refrigeration	Install an additional underground refrigeration plant to the current system.	Increase the cooling capacity and stabilise the cold dam temperature.
A ₁₀	Intake air BAC (Decline)	Install a BAC in the main decline haulage.	Cool the air from the surface to offset the auto-compression.
A ₁₁	Intake air BAC (1C sub-shaft)	Install a BAC in the intake air of the 1C# haulage.	Cool the air from the surface to offset the auto-compression.
A ₁₂	Surface refrigeration	Install a surface refrigeration plant to cool some of the air going underground.	Create winter conditions all year round by sending cooler air underground. Decrease (counter) the air's heating capabilities through offsetting auto-compression.
A ₁₃	Electric vehicles	Change the diesel machinery to electric vehicles.	Lower the mechanised heat load.
A ₁₄	291 Chill pond	Install a chill pond on 291 level.	Improve the positional efficiency of the cooling circuit by moving the cooling closer to the mining block.

The six projects shown in Table 3-3 will be further evaluated in Step 2. More elaborate details on the ventilation and cooling projects can be found in Appendix C: Project detail.

The main objective of Step 1 was accomplished by collecting the information, baselining the system, developing a simulation model, and identifying all the projects that can improve the underground environment of the case study mine.

3.2.3 Step 2: Evaluate projects

Step 2 will use the information collected in the previous step to evaluate the projects and set up the decision matrix at the end of the step. Step 2's phase division is highlighted in blue in Figure 3-13.

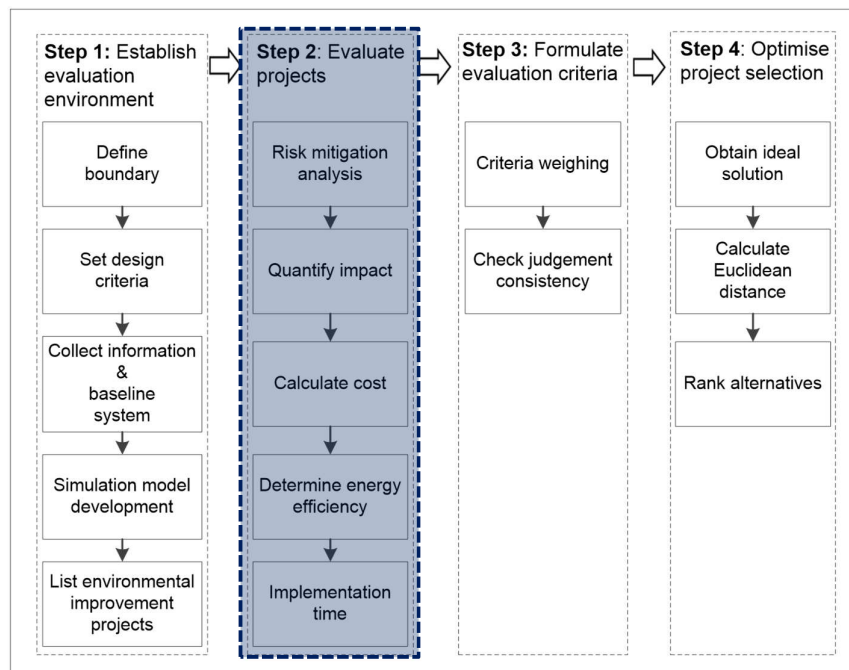


Figure 3-13: Step 2 of the methodology – Evaluate projects

This step will evaluate the projects according to the evaluation criteria before the next step, where the MCDM processes are used to select the most suitable project.

Risk mitigation analysis

The evaluation, based on risk mitigation by the proposed projects, is the next step. The mine personnel identified the main risks that the mine faces as:

- The mining block is situated six kilometres from the intake shaft.
- The mine has only one intake and return airway. The main RAW, the mine is dependent on, is in bad condition and inaccessible.
- Most of the return is through the old working areas of a closed mine, and the area is inaccessible.

The areas associated with these risks listed above can be seen in Figure 3-14.

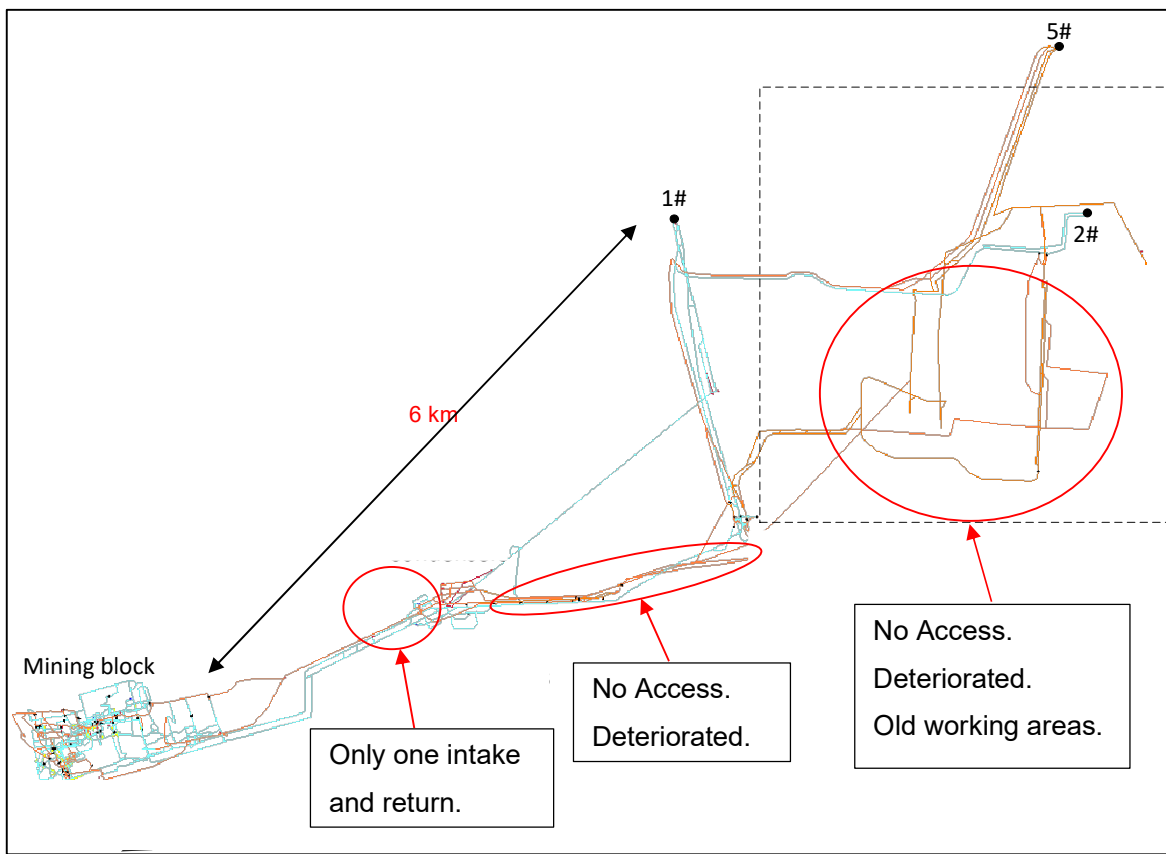


Figure 3-14: Mine's highest risks - Visual indication

The risk matrix selected in Table 2-4 is used to give a monetary value to the consequence of not implementing the project and the probability that risk can occur. The explanation for the consequence and probability values is described in Table 3-5.

Table 3-5: Risk analysis for each project

Symbol	Project	Risk factor	Explanation			
			Consequences	Rating	Probability	Rating
A ₁	Additional/ new shaft	12	Only one return and intake to the mining block, which is 6 km away – Will close the mine if the return or intake collapses.	4	RAW has various FOG with no support and high temperature, high humidity airflow.	3
A ₂	Cross-over	9	Main Return to 5#, which will close off a large section. Would have to suspend mining activities for up to 2 weeks.	3	RAW has various FOG with no support and high temperature, high humidity airflow.	3
A ₃	Condenser 5	2	If a booster fan fails, the return quantity can lower, this can be easily corrected. Start mining within the same day.	1	Unlikely that all five booster fans will fail.	2
A ₄	Additional fans in the RAW	6	Failure of mining block fans or booster fans can negatively affect mining. Production loss.	2	Mining fans fail frequently.	3
A ₅	New straight RAW to 1#	12	Only one return and intake to the mining block, which is 6 km away – Will close the mine if the return or intake collapses.	4	RAW has various FOG with no support and high temperature, high humidity airflow.	3
A ₆	Rehabilitate the current RAW	9	Main Return to 5#, which will close off a large section. Would have to suspend mining activities for up to 2 weeks.	3	RAW has various FOG with no support and high temperature, high humidity airflow.	3
A ₇	Additional RAW to 5#	12	Only one return and intake to the mining block, which is 6km away – Will close the mine if the return or intake collapses.	4	RAW has various FOG with no support and high temperature, high humidity airflow.	3
A ₈	Additional intake and return haulage	12	Only one return and intake to the mining block, which is 6km away – Will close the mine if the return or intake collapses.	4	RAW has various FOG with no support and high temperature, high humidity airflow.	3
A ₉	Underground refrigeration	6	Possible high temperatures when one refrigeration plant fails can start multiple plants. Can cause production loss.	2	Likely to happen.	3
A ₁₀	Intake air BAC (Decline)	9	Continually high temperatures underground. More than 2 days without mining activities.	3	Likely to happen.	3
A ₁₁	Intake air BAC (1C sub-shaft)	9	Continually high temperatures underground. More than 2 days without mining activities.	3	Likely to happen.	3
A ₁₂	Surface refrigeration	9	Continually high temperatures underground. More than 2 days without mining activities.	3	Likely to happen.	3
A ₁₃	Electric vehicle	12	When legislation is implemented the capital cost to change the diesel machinery will be too high to change immediately	4	Legislation changes likely.	3
A ₁₄	291 Chill pond	8	High temperatures at that specific working area.	2	Certain for high temperatures.	4

Table 3-5 indicated that five of the 14 projects rated as very high-risk, six projects rated high-risk, two rated medium-risk and one obtained a low-risk rating. The impact on the underground environment will be assessed in the next step.

Quantify impact

The simulation model developed in Step 1 is used in these criteria to determine the impact of the projects.

All the proposed projects from Table 3-3 and Table 3-4 were implemented. The changes to the baseline simulation model can be seen in Appendix D: Quantify impact detail. The impact was simulated, and at the location mentioned in Table 3-1 and Figure 3-8, the velocity and temperature values were exported, and

Equation 2-1 was used to calculate the ACP.

The project's improvement is calculated by totalling the levels' ACP and comparing it to the baseline value. The summary of these values is shown in Table 3-6.

Table 3-6: Project environmental impact

Symbol	Project	Change in ACP (W/m ²)
A ₁	Additional/new shaft	311.2
A ₂	Cross-over	18.1
A ₃	Condenser 5	205.7
A ₄	Additional fans in the RAW	480.8
A ₅	New straight RAW to 1#	66.3
A ₆	Rehabilitate the current RAW	44.2
A ₇	Additional RAW to 5#	102.5
A ₈	Additional intake and return haulage	22.4
A ₉	Underground refrigeration	397.9
A ₁₀	Intake air BAC (Decline)	703.7
A ₁₁	Intake air BAC (1C sub-shaft)	32.6
A ₁₂	Surface refrigeration	770.2
A ₁₃	Electric vehicle	61.7
A ₁₄	291 Chill pond	194.4

More detail of the ACP values in Table 3-6 for each level of the projects are shown in Appendix D: Quantify impact detail. Table 3-6 shows that surface refrigeration (A₁₂) has the most significant impact on the underground environment, while cross-over (A₂) has the most negligible impact on the underground environment. The cost analysis of each project follows next.

Calculate cost

The capital cost was determined by obtaining quotes, and Table 3-7 shows the summary of the capital cost.

Table 3-7: Capital cost for the projects

Symbol	Project	Capital cost (R)
A ₁	Additional/new shaft	374 193 000
A ₂	Cross-over	22 069 000
A ₃	Condenser 5	25 430 000
A ₄	Additional fans in the RAW	48 000 000
A ₅	New straight RAW to 1#	219 739 000
A ₆	Rehabilitate the current RAW	21 174 000
A ₇	Additional RAW to 5#	494 838 000
A ₈	Additional intake and return haulage	817 091 000
A ₉	Underground refrigeration	16 315 000
A ₁₀	Intake air BAC (Decline)	44 390 000
A ₁₁	Intake air BAC (1C sub-shaft)	38 582 000
A ₁₂	Surface refrigeration	46 605 000
A ₁₃	Electric vehicle	99 000 000
A ₁₄	291 Chill pond	17 989 000

Table 3-7 is only the summary table of the capital cost, with more detail about each project can be found in Appendix E: Detailed cost analysis.

Energy efficiency

PTB can calculate the power usage of the project and compare it with the baseline. The baseline's annual power usage is 116.6 GW. Based on the baseline, the increase in power usage by implementing the project is shown in Table 3-8.

Table 3-8: Difference in power usage of the projects.

Symbol	Project	Energy efficiency (GW)
A ₁	Additional/new shaft	13.266
A ₂	Cross-over	-0.401
A ₃	Condenser 5	7.953
A ₄	Additional fans in the RAW	3.430
A ₅	New straight RAW to 1#	-0.706
A ₆	Rehabilitate the current RAW	-0.614
A ₇	Additional RAW to 5#	1.116
A ₈	Additional intake and return haulage	2.797
A ₉	Underground refrigeration	18.970
A ₁₀	Intake air BAC (Decline)	21.465
A ₁₁	Intake air BAC (1C sub-shaft)	20.668
A ₁₂	Surface refrigeration	18.527
A ₁₃	Electric vehicle	0.203
A ₁₄	291 Chill pond	1.730

The negative energy efficiency values in Table 3-8 are because the project uses less power than the baseline project. The annual power usage of each project can be seen in Appendix F: Project power usage.

Implementation time

The implementation time of each project is calculated based on previous projects of the same size, calculated using current development rates and prospective contractors. Table 3-9 shows the implementation time of each project.

Table 3-9: Implementation time of the proposed projects

Symbol	Project	Implementation time (Months)
A ₁	Additional/new shaft	36
A ₂	Cross-over	9
A ₃	Condenser 5	8
A ₄	Additional fans in the RAW	18
A ₅	New straight RAW to 1#	27
A ₆	Rehabilitate the current RAW	6
A ₇	Additional RAW to 5#	57
A ₈	Additional intake and return haulage	60
A ₉	Underground refrigeration	3
A ₁₀	Intake air BAC (Decline)	8
A ₁₁	Intake air BAC (1C sub-shaft)	6
A ₁₂	Surface refrigeration	6
A ₁₃	Electric vehicle	48
A ₁₄	291 Chill pond	8

Final evaluation table

Table 3-10 summarises the information collected for the criteria in Step 2.

Table 3-10: Projects' evaluation values

Symbol	Risk assessment	Impact (W/m ²)	Cost (R M)	Energy efficiency (GW)	Implementation time (Months)
A ₁	12	311.2	374	13.27	36
A ₂	9	18.1	22	-0.40	9
A ₃	2	205.7	25	7.95	8
A ₄	6	480.8	48	3.43	18
A ₅	12	66.3	220	-0.71	27
A ₆	9	44.2	21	-0.61	6
A ₇	12	102.5	495	1.12	57
A ₈	12	22.4	817	2.80	60
A ₉	6	397.9	16	18.97	3
A ₁₀	9	703.7	44	21.46	8
A ₁₁	9	32.6	39	20.67	6
A ₁₂	9	770.2	47	18.53	6
A ₁₃	12	61.7	99	0.20	48
A ₁₄	8	194.4	18	1.73	8

The projects are now evaluated based on the five criteria. In Step 3, the criteria will be weighted, and in Step 4, the projects will be ranked.

3.2.4 Step 3: Formulate evaluation criteria

This step will formulate the weights of the criteria used in Step 2 to evaluate the projects. The AHP is used to allocate the weights to the respective criteria. Figure 3-15 shows Step 3's two phases in blue which will be applied here.

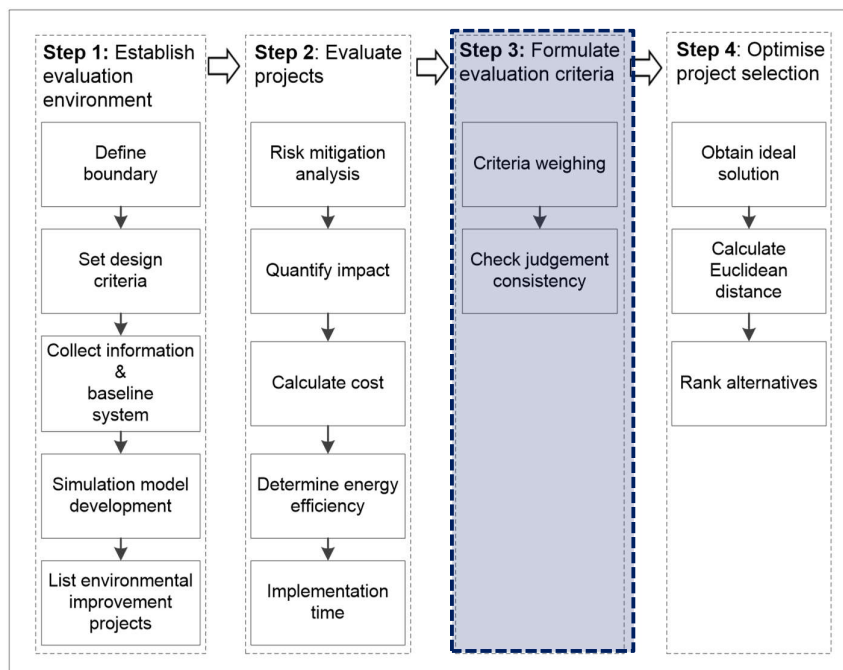


Figure 3-15: Step 3 of the methodology – Formulate evaluation criteria

Criteria weighting

The literature showed that there should be a balance between risk mitigation and the benefit of the project. The criteria weights were determined using the criteria order, as stated in the method's Step 3 and the pairwise-comparison scale in Table 2-8.

Allocating pairwise comparison values

A meeting with the mine's management team was arranged to use the pairwise comparison scale to allocate the values to the criteria. The values can be seen in Table 3-11.

Table 3-11: Values allocated during the criteria weighting

Comparison criteria	Value	Definition
Risk vs Impact	2	Risk is slightly favoured above impact
Risk vs Cost	3	Risk is slightly more favoured above cost
Risk vs Power	5	Risk is strongly favoured above power
Risk vs Time	9	Risk is strongly and dominance favoured above time
Impact vs Cost	3	Impact is slightly more favoured above cost
Impact vs Power	5	Impact is strongly favoured above power
Impact vs Time	7	Impact is favoured highly above time
Cost vs Power	1	Cost and power are equal in value
Cost vs Time	3	Cost is slightly favoured above time
Power vs Time	3	Power is slightly favoured above time

These values in Table 3-11 were then used to construct the judgement matrix. Figure 3-16 shows the judgement matrix used for the decision-making process.

	Risk	Impact	Cost	Power	Time
Risk	1	2	3	5	9
Impact	$\frac{1}{2}$	1	3	5	7
Cost	$\frac{1}{3}$	$\frac{1}{3}$	1	1	3
Power	$\frac{1}{5}$	$\frac{1}{5}$	1	1	3
Time	$\frac{1}{9}$	$\frac{1}{7}$	$\frac{1}{3}$	$\frac{1}{3}$	1

Figure 3-16: The mine's judgement matrix

The judgement matrix is then normalised using Equation 2-4. After the matrix is normalised, the relative weights are calculated using Equation 2-5. Table 3-12 shows the relative weight of the criteria.

Table 3-12: Criteria weight

C ₁	C ₂	C ₃	C ₄	C ₅
0.43	0.31	0.12	0.10	0.04

Table 3-12 can also be represented as a criteria vector; $W = [0.43, 0.31, 0.12, 0.10, 0.04]$. The following step will establish if the judgement matrix is acceptable and reasonable.

Check judgement consistency

The consistency vector (CV) is calculated using Equation 2-7. Figure 3-17 shows the consistency vector.

$$[CV] = [A] \cdot [W] = \begin{bmatrix} 1 & 2 & 3 & 5 & 9 \\ 0.50 & 1 & 3 & 5 & 7 \\ 0.33 & 0.33 & 1 & 1 & 3 \\ 0.20 & 0.20 & 1 & 1 & 3 \\ 0.11 & 0.14 & 0.33 & 0.33 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.43 \\ 0.31 \\ 0.12 \\ 0.10 \\ 0.04 \end{bmatrix} = \begin{bmatrix} 2.25 \\ 1.64 \\ 0.58 \\ 0.48 \\ 0.20 \end{bmatrix}$$

Figure 3-17: The consistency vector

The consistency vector calculated in Figure 3-17 can now be used with Equation 2-8 to calculate the eigenvalue of each criterion.

Table 3-13: Eigenvalues

i	λ_i
1	5.19
2	5.20
3	5.03
4	5.03
5	5.07

The maximum eigenvalue (λ_{max}) is then calculated using Equation 2-9 to give λ_{max} as 5.11, the maximum eigenvalue is then used in Equation 2-10 to determine the CI. The CI was calculated as 0.026, and the CR of 0.023 was calculated using Equation 2-11.

The CR value is 2.3%, which is in the comfortable zone to not recreate the judgement matrix because of the judgement consistency. The criteria are now successfully weighted using the AHP method.

3.2.5 Step 4: Optimise project selection

The final step, Step 4, is to rank the projects. In this step, the TOPSIS method will be used to rank all the projects in Table 3-3 and Table 3-4. Figure 3-18 shows the last step of this method.

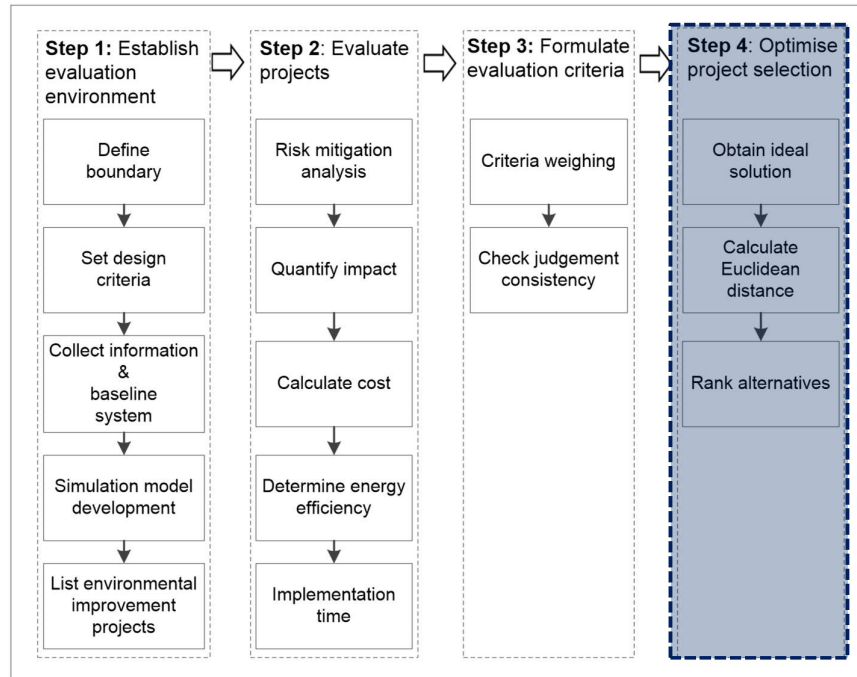


Figure 3-18: Step 4 of the methodology – Optimise project selection

The blue block in Figure 3-18 indicates the phases for Step 4. The decision matrix of Table 3-10 and the weighted criteria in Table 3-12 will be used during this step.

Obtain ideal solution

The weighted normalised decision matrix is calculated using Equation 2-13, and the values from Table 3-10 form the decision matrix (R_{ij}) which is used. The start is to normalise ($\bar{R}_{ij}$) the decision matrix using Equation 2-4. Table 3-14 is the normalised decision matrix.

Table 3-14: Normalised decision matrix ($\bar{R}_{ij}$)

Project	C ₁	C ₂	C ₃	C ₄	C ₅
W	0.43	0.31	0.12	0.10	0.04
A ₁	0.337	0.240	0.353	0.311	0.311
A ₂	0.253	0.014	0.021	0.007	0.007
A ₃	0.056	0.159	0.024	0.193	0.193
A ₄	0.169	0.371	0.045	0.092	0.092
A ₅	0.337	0.051	0.208	0.000	0.000
A ₆	0.253	0.034	0.020	0.002	0.002
A ₇	0.337	0.079	0.468	0.041	0.041
A ₈	0.337	0.017	0.772	0.078	0.078
A ₉	0.169	0.307	0.015	0.438	0.438
A ₁₀	0.253	0.543	0.042	0.494	0.494
A ₁₁	0.253	0.025	0.037	0.476	0.476
A ₁₂	0.253	0.595	0.044	0.428	0.428
A ₁₃	0.337	0.048	0.094	0.020	0.020
A ₁₄	0.225	0.150	0.017	0.054	0.073

The normalised decision matrix is weighted by multiplying the weight of the criteria with the column values. Table 3-15 shows the values from the weighted normalised matrix.

Table 3-15: Weighted normalised decision matrix (V_{ij})

Project	C ₁	C ₂	C ₃	C ₄	C ₅
A ₁	0.146	0.076	0.041	0.030	0.013
A ₂	0.110	0.004	0.002	0.001	0.000
A ₃	0.024	0.050	0.003	0.018	0.008
A ₄	0.073	0.117	0.005	0.009	0.004
A ₅	0.146	0.016	0.024	0.000	0.000
A ₆	0.110	0.011	0.002	0.000	0.000
A ₇	0.146	0.025	0.054	0.004	0.002
A ₈	0.146	0.005	0.089	0.007	0.003
A ₉	0.073	0.097	0.002	0.042	0.018
A ₁₀	0.110	0.171	0.005	0.047	0.020
A ₁₁	0.110	0.008	0.004	0.046	0.019
A ₁₂	0.110	0.187	0.005	0.041	0.017
A ₁₃	0.146	0.015	0.011	0.002	0.001
A ₁₄	0.097	0.047	0.002	0.005	0.003

The weighted normalised matrix can now be used to calculate the Euclidean distance in the next phase.

Calculate Euclidean distance

The PIS (V^*) for the risk and impact is the highest value, while the PIS for cost, energy efficiency and time is the lowest value. Equation 2-14 is used to calculate the PIS of each criterion and Table 3-16 shows the PIS for the criteria.

Table 3-16: PIS for the criteria (V^*)

	C_1	C_2	C_3	C_4	C_5
Attributes	Max	Max	Min	Min	Min
Value	0.146	0.187	0.002	0.0	0.0

The V^* in Table 3-16 can be indicated as $\{0.146, 0.187, 0.002, 0.0, 0.0\}$. The NIS (V^-) is the worst performance score, and this is the minimum value for risk and impact, while this is the maximum value for cost, energy efficiency and time. Equation 2-15 is used to calculate the NIS of each criterion and Table 3-17 shows the NIS for the criteria.

Table 3-17: NIS for the criteria (V^-)

	C_1	C_2	C_3	C_4	C_5
Attributes	Min	Min	Max	Max	Max
Value	0.024	0.004	0.089	0.047	0.020

The V^- in Table 3-17 can be indicated as $\{0.024, 0.004, 0.089, 0.047, 0.02\}$. The Euclidean distance can now be calculated using Equation 2-16 to determine the project distance to the PIS and Equation 2-17 to determine the project distance to the NIS.

Table 3-18: Project's distance to the PIS and NIS

Project	D_i^*	D_i^-
A ₁	0.119	0.149
A ₂	0.187	0.123
A ₃	0.184	0.098
A ₄	0.102	0.149
A ₅	0.173	0.140
A ₆	0.180	0.124
A ₇	0.171	0.130
A ₈	0.202	0.123
A ₉	0.118	0.136
A ₁₀	0.045	0.205
A ₁₁	0.184	0.120
A ₁₂	0.041	0.219
A ₁₃	0.173	0.147
A ₁₄	0.148	0.130

The distances to the NIS and PIS can be used in the last phase of Step 4 to rank the projects.

Rank the projects

The relative closeness (C_i^*) should be calculated using Equation 2-18 to rank the projects for the mine. Table 3-19 shows the relative closeness of the projects and contains the ranking.

Table 3-19: Relative closeness (C_i^*) and rank

Project	C_i^*	Rank
A ₁	0.557	4
A ₂	0.398	11
A ₃	0.349	14
A ₄	0.595	3
A ₅	0.448	8
A ₆	0.407	10
A ₇	0.432	9
A ₈	0.379	13
A ₉	0.536	5
A ₁₀	0.821	2
A ₁₁	0.395	12
A ₁₂	0.844	1
A ₁₃	0.459	7
A ₁₄	0.467	6

Table 3-19 shows the ranking of the projects in the third column. Table 3-20 shows the projects ranked in order of preference.

Table 3-20: Projects ranked in order of preference

Rank	Symbol	Project
1	A ₁₂	Surface refrigeration
2	A ₁₀	Intake air BAC (Decline)
3	A ₄	Additional fans in the RAW
4	A ₁	Additional/new shaft
5	A ₉	Underground refrigeration
6	A ₁₄	291 Chill pond
7	A ₁₃	Electric vehicle
8	A ₅	New straight RAW to 1#
9	A ₇	Additional RAW to 5#
10	A ₆	Rehabilitate the current RAW
11	A ₂	Cross-over
12	A ₁₁	Intake air BAC (1C sub-shaft)
13	A ₈	Additional intake and return haulage
14	A ₃	Condenser pond 5

Table 3-20 shows that the Surface Refrigeration (A₁₂) is the most suitable project to implement, while the Condenser pond 5 (A₃) project is the least suitable. The top half of the projects ranked in

Table 3-20; indicate that the projects ranked one to seven consist of five projects related to cooling, with only two projects related to ventilation. The lower half of the ranked projects comprises six projects relating to ventilation and only one (A_{11}) related to cooling projects. A more detailed discussion of the results shown in Table 3-20 will follow.

Implementation

The proposed method was applied to the case study mine, and the project ranked first; the Surface Refrigeration (A_{12}) was implemented.

The Surface Refrigeration (A_{12}) was installed to link into the main downcast through an old ducting used during the shaft development. The aerial view of the site layout is shown in Figure 3-19.



Figure 3-19: Aerial view of the planned location for the surface refrigeration project

The process of developing the project plan, applying for funding, undertaking the tender process, and installing the whole project was planned for completion in six months; however, delays in procurement delayed completion from February to May 2021. Figure 3-20 shows the surface refrigeration installed in the mine.

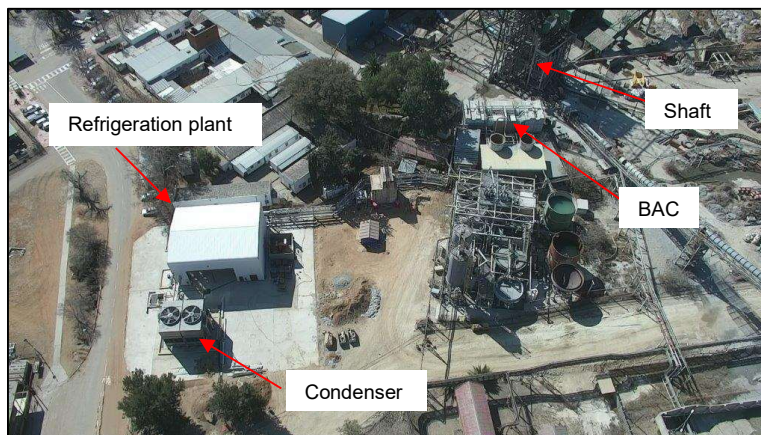


Figure 3-20: Surface refrigeration installed at the case study mine

3.3 Result analysis

This Section will elaborate on the ranking process and results of the method developed in this thesis. Further analysis will be done on the ranking's outcome if the decision-making process has been financially motivated.

3.3.1 MCDM process

The results from the case study will be examined in more detail to establish how the MCDM method ranked these projects. The graph in Figure 3-21 compares the ranking with the risk rating allocated to the project and the impact on the underground environment.

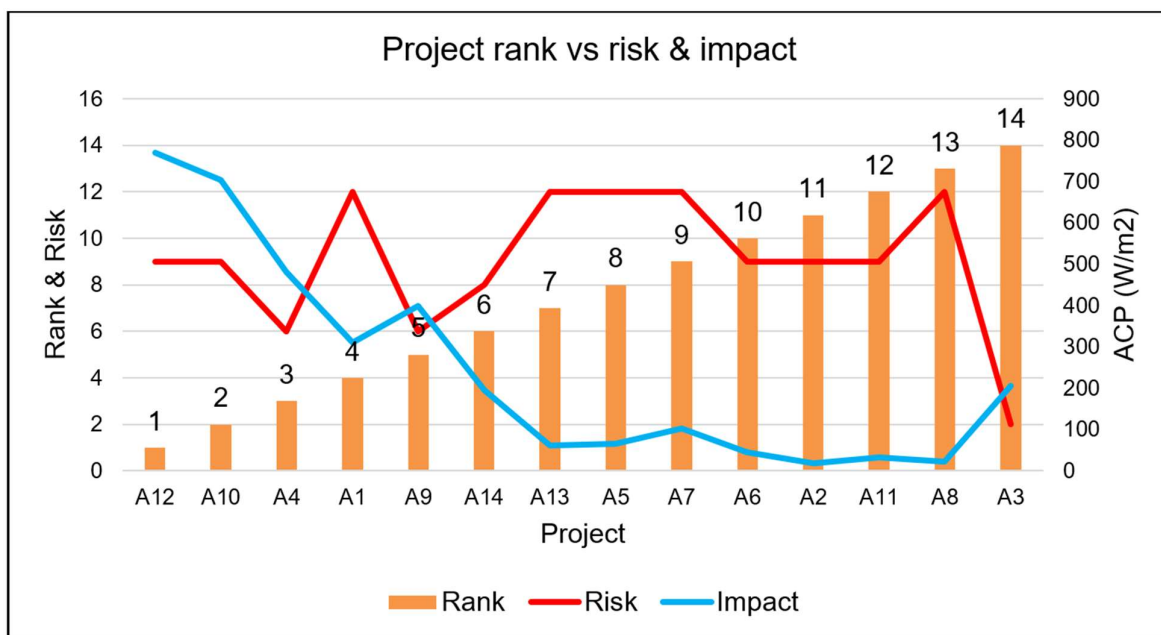


Figure 3-21: Projects comparison graph of the MCDM results

Figure 3-21 illustrates that projects A₁₂, A₁₀ and A₄, the highest impact projects, were preferred as these projects occupied ranks one to three. The influence of the risk criteria is shown with the ranking of A₁ (Additional/new shaft) in fourth place and A₉ (Underground refrigeration) in fifth place. The risk value played an essential role between these two projects; therefore, A₁ was ranked higher than A₉, although it has a higher impact.

The other criteria's influence can be seen when project A₇ (Additional RAW to 5#), ranked ninth, has a higher impact but the same risk value than the projects ranked before A₇ (Projects A₁₃ and A₅). Project A₇ has one of the highest costs, with an energy efficiency increase above projects A₁₃ and A₅. This is also noticeable as projects ranked 10, 11 and 12 (A₆, A₂ and A₁₁) are ranked higher than the project ranked thirteenth (A₈), which has a higher risk value.

Project A₃'s impact would have ranked the project sixth, but due to the low-risk value, A₃ is ranked last.

3.3.2 Comparison with Cost-benefit analysis

The comparison between the ranking of projects using the developed method and the usual financial-driven “ranking” decision process is shown in Figure 3-22.

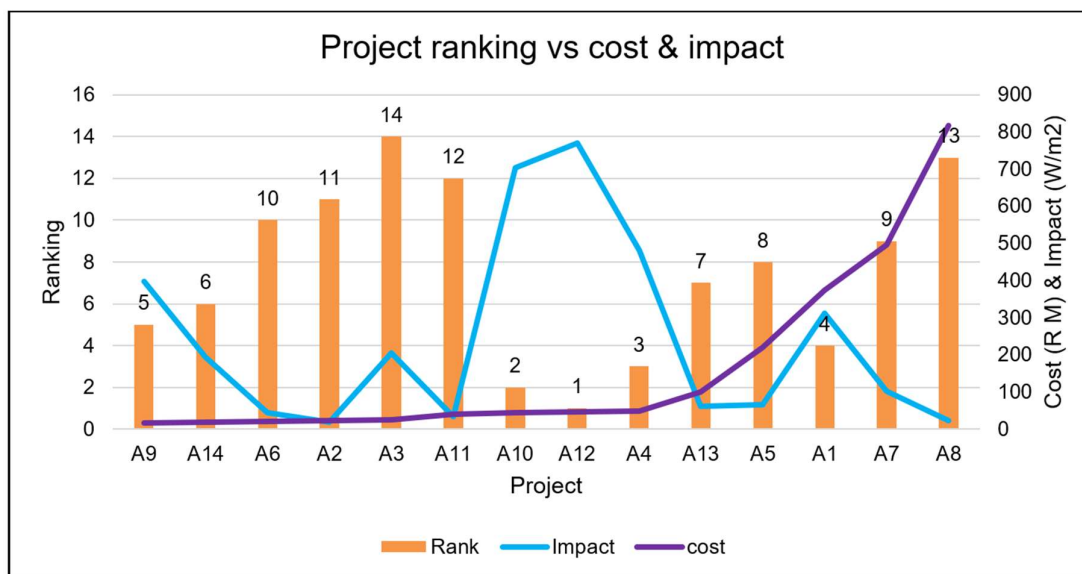


Figure 3-22: Projects ranking against the cost and impact

Figure 3-22 illustrates the ranking if the decision-making process would have been financially motivated. Projects A₉, A₁₄, and A₆ would have been the preferred projects to implement since they are the cheapest, and projects A₇ and A₈ would have been the least preferred option.

Comparing the ranking of Table 3-20 (the orange bars in Figure 3-22) to the ranking in Figure 3-22, Figure 3-22 shows that the projects ranked fifth, sixth and tenth, using the developed method, are the projects that would have been chosen first to be implemented if the decision was financially motivated. The first ranked project in Figure 3-22 would not be the worst option since it is the cheapest and has a respectable impact on the underground environment but has a low-risk value of five.

The problem here shows that the projects ranked third to fifth in Figure 3-22 have minor impacts on the underground environment and is the lowest-ranked projects in Table 3-20.

The mine started by implementing Condenser pond 5, while Table 3-20 shows that A₃ is ranked fourteenth, based on the criteria used in this method. Although project A₃ is one of the less expensive options, the risk rating and impact of the project on the underground environment are low.

3.4 Validation

The definition of validation:

Validation refers to if the method developed in Chapter 2 delivers the correct answer for the needs of this study identified in Section 1.8.³

The validation of the method will be divided into two sections; the project selected without the developed method and the new method's accuracy. The new method developed in Chapter 2 will be validated through these sections.

Mine selected project

This section will elaborate on the project the mine implemented before the method developed in this thesis was applied. The mine used financial-driven and non-scientific processes in an attempt to solve its underground ventilation and cooling problems.

The mine personnel recognised that they struggle to supply the underground environment with the necessary ventilation and cooling to stay below the legal temperature, as stated in Table 1-1. The mine attempted to develop an idea to improve the underground environment at the lowest possible cost. According to their experience, the mine personnel knew their problem was caused by insufficient cooling and ventilation at the working places, and they needed to increase the cooling or ventilation to solve the underground environmental issues.

(i) Decision

The mine made a list of possible projects, but since the mine does not have simulation software, the possible holistic impact of the projects could not be evaluated. The list of possible projects is presented in Table 3-21.

³ Definition from North-West University's Masters marking paper

Table 3-21: Possible projects to improve the mine

Possible solution	Cooling	Ventilation	Capital cost
Surface Refrigeration	X		R 46 605 000
Condenser pond 5	X	X	R 25 430 000
Underground Refrigeration	X		R 16 315 000
New Shaft		X	R 374 193 000
Cross-over		X	R 22 069 000

The solution selected was the Condenser pond 5 since, according to experience, it will increase the refrigeration circuit's cooling capabilities and the air through the mining process. This solution addressed both the cooling and ventilation issues. The mine's calculation shows that Condenser pond 5 will increase the return capacity from 197 kg/s to 246 kg/s. The next step is implementing the booster fan.

(ii) Implementation of Condenser pond 5

The implementation was planned for 2017, but delays in the development of the condenser chamber led to the completion only in 2022. The shotcrete of the chamber can be seen in Figure 3-23.



Figure 3-23: Condenser chamber with shotcrete

The completed pumping station can be seen in Figure 3-24, with the completed booster fan in Figure 3-25.



Figure 3-24: Condenser pond 5 pumping station



Figure 3-25: Condenser pond 5 booster fan

The booster fan was commissioned in June 2022. A ventilation survey was done in the main RAW to establish that more air is returning from the mining block.

Table 3-22: RAW total mass flow before and after CP5 implementation

Description	Before CP5	After CP5
Mass flow (kg/s)	197	217

Table 3-22 shows that the booster fan implementation did not deliver the 246 kg/s as expected but 29 kg/s lower. The Condenser pond 5 booster fan was influencing the other four booster fans already operating close to their stall zone, and this pressured the engineer to stop booster fan 5 and use the booster fan with the condenser pond only for redundancy.

The mine's financial-driven solution without any method showed crucial shortcomings, such as:

- Not using simulation software to determine the project impact on the holistic mine network.

- Not using a scientific method to select the most suitable option.
- Not considering other criteria.
- Substantial bias influenced the final decision.

If the mine used the method developed in this thesis, the mine would have selected the most suitable project based on a science and literature-backed method that evaluates projects based on multiple criteria. The simulations model developed in Step 1 of the ranking method used to determine the impact of the projects in Step 2 evaluates the project's impact on the holistic ventilation network that would have prompted the mine on the problem beforehand. Steps 3 and 4 assist in selecting the most efficient option based on the various weighted criteria. The shortcomings of the process used by the mine to select the project wasted vital resources on the wrong project.

Surface refrigeration

The surface refrigeration project was ranked first in Table 3-20, and the mine implemented the project based on the recommendations of the developed method. This section will elaborate on the method's accuracy for predicting the results and ranking the projects.

A ventilation audit was done on 25 January 2022 when the surface refrigeration was running. The information can be seen in Table 3-23.

Table 3-23: The surface refrigeration project's audit data

Ref.	Level	Mass flow (kg/s)	Velocity (m/s)	Wet-bulb Temp (°C)	Dry-bulb Temp (°C)	ACP (W/m ²)
F	272	17.8	1.11	23.6	26.1	861.5
H	280	12.0	0.75	29.2	31.05	216.8
I	273	5.6	0.35	28.1	30.9	135.1
K	284	17.9	1.12	27.2	29.5	643.4
L	287	10.7	0.80	29.6	33.4	195.5
M	289	8.4	0.42	30.3	31.5	127.7
N	291	21.1	1.45	30.8	30.5	983.1

The accuracy of the model's prediction ability can be verified by comparing the predicted impact with the actual measured values from the audit in Table 3-23. The comparison of the simulated and actual values is shown in Table 3-24.

Table 3-24: Surface refrigeration actual results comparison

Ref.	Level	Simulated impact ACP (W/m ²)	Actual measured ACP (W/m ²)
F	272	669.8	861.5
H	280	350.9	216.8
I	273	459.9	135.1
K	284	520.7	643.4
L	287	383.1	195.5
M	289	328.4	127.7
N	291	399.9	983.1
MB inlet total		3 112.7	3 163.2
Δ ACP		770.1	820.5

The total inlet ACP is almost the same and only varies by 50.5 W/m². The distribution of the ACP through the mine is different from predicted since some operational challenges changed the airflow distribution. The 267 level BAC was only running at 50% capacity, impacting the 280 level (H) and 273 level (I). Each of the lower levels, 287 (L) and 289 (M), had an in-operational fan due to breakdowns. Even with these operational challenges, Table 3-24 shows that the change in ACP between the simulated and actual differs by 6%. This is in an acceptable margin to verify that the simulation model gives accurate results.

The capital 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 56 439 000. Changes to the original idea of running the Surface Refrigeration were refined, and the energy efficiency profile changed from the worst-case scenario to only operating for seven months (September to March) of the year. The increase in energy efficiency from the base was calculated to be 9.456 GW. The proposed implementation time for the project was six months, but from the start until the commissioning of the Surface Refrigeration project took two months longer than predicted. Table 3-25 summarises the predicted and actual values of the Surface Refrigeration project.

Table 3-25: Surface Refrigeration predicted compared to actual values

Criteria	Model predicted values	Actual values
Risk	9	9
Impact (W/m ²)	770.1	820.5
Cost (R M)	46,6	56,4
Energy efficiency (GW)	18.527	9.456
Implementation time (Months)	6	8

The actual values summarised in Table 3-25 were used in Table 3-10, projects' evaluation values, with the other values and Step 3 and Step 4 were redone to ascertain the impact these changes will have on the ranking of the projects.

The ranking order of the projects stayed the same, with the surface refrigeration project still ranked first. This section shows that the method developed can accurately predict the results and ranking of the projects.

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

3.5 Conclusion

The method developed in Chapter 2 was implemented in a case study mine in this Chapter. In Step 1, all the information was collected, the simulation model developed, and a list of 14 projects was established.

The simulation model was used to evaluate the project to determine the impact, in addition to the four other criteria used during the evaluation step.

The risk was weighted the highest, with impact close second in Step 3 using the AHP. In Step 4, the TOPSIS method was applied to rank the projects from the most suitable to the least suitable based on the five criteria. The Surface Refrigeration, A₁₂, was ranked first, while the Condenser pond 5, A₃, was ranked last.

The method was validated by using a non-scientific method to identify and solve their underground cooling and ventilation problems. The mine implemented the Condenser pond 5 project, the last

ranked project, that only serves as redundancy to the condenser system on 255 level. The validation was strengthened by comparing the Surface Refrigeration project's actual values to the predicted ones, and the new method still ranked the Surface Refrigeration project first.

The case study showed how valuable the method developed in this thesis could be to focus on important projects and not spend precious resources on insignificant projects.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Study summary

The literature study conducted as part of this thesis established that a non-scientific method is followed in the decision-making process for ventilation and cooling projects in underground mines, but bias and experience still rule the decision-making process. MCDM methods were suggested to make the decision-making process less prone to bias, open to evaluating two systems with multiple criteria and more scientific.

A need was established for a method to assist decision-makers in evaluating various environmental improvement projects and using a scientific process to rank these projects. The thesis aimed to develop such a method using MCDM for the ranking. Simulations were also incorporated with the MCDM method to evaluate the holistic underground ventilation and cooling system accurately.

The proposed method was developed in Chapter 2 and consisted of four steps. Step 1 establishes the evaluation environment through five phases, and results in a list of proposed projects to improve the underground environment. In Step 2, the projects are evaluated according to the five criteria: risk mitigation, impact, cost, energy efficiency and time. Step 3 weights the criteria using the AHP method, while step 4 uses the TOPSIS method to rank the projects according to suitability.

The method was applied to a case study mine in Chapter 3 to assist in evaluating environmental improvement projects. The mine struggled to supply adequate ventilation and cooling to their underground environment. The project ranked the highest was Surface Refrigeration, while the Condenser pond 5 project was ranked the lowest. The mine was busy implementing Condenser pond 5 at the time, and it served purely as a redundancy. The implemented Surface Refrigeration option, identified by the study's method, was proven effective and validated that the predicted results of the method are accurate.

The method proved that it could evaluate various ventilation and cooling projects to improve the underground environment and rank these projects so that the most suitable project can be selected.

An article based on the developed method was published in the Mining, Metallurgy & Exploration journal titled "*Prioritisation of environmental improvement projects in deep-level mine ventilation system*" [143]. Proof of publication is in Appendix G: Published article .

4.2 Novel contributions

The novel contributions, stated in Section 1.9, were addressed in this study as follows:

4.2.1 Novel contribution 1

Developing a method that evaluates and ranks various environmental improvement projects in operational deep-level underground mines.

The first part of the proposed method developed in Chapter 2, Figure 2-16, consisted of establishing the evaluation environment to evaluate the ventilation and cooling system of a mine and identifying projects that will improve the underground's thermal environment. The second part uses scientific methods to rank these projects from the most suitable to the least suitable. The method is illustrated through a case study in Chapter 3, which evaluates 14 projects and ranks the projects according to priority.

4.2.2 Novel contribution 2

Use multi-criteria decision-making (MCDM) methods to rank underground environmental improvement projects.

The method developed in Chapter 2's second part uses a hybrid MCDM method, especially AHP, to weigh the criteria and TOPSIS to rank the underground environmental improvement projects. In Chapter 3, these methods were applied to the case study. While implementing the method, it was noticed that the mine had already started implementing other projects; however, the least applicable project was chosen due to decision-maker's preference. This incident highlighted that a scientific method such as MCDM should be the preferred method to incorporate during decision-making.

4.2.3 Novel contribution 3

Using ventilation simulations in combination with MCDM methods to evaluate and prioritise the impact of each project on the complex underground ventilation system.

Incorporating ventilation simulations into the MCDM method will increase the accuracy of the ventilation and cooling projects' impact on the complex underground environment. Step 2 in Figure 2-16, the impact of the projects is determined using a calibrated simulation model. The simulation model can evaluate a project's impact on the holistic ventilation and cooling system.

4.3 Conclusion

The study's objectives were achieved by developing a method to evaluate and rank environmental improvement projects. Based on the case study, the developed method is valuable for evaluating

environmental improvement projects, and proof is provided through implementation of the most suitable projects.

Using simulations to calculate the impact is an asset in improving the accuracy of the decision-making process. By ranking the projects using MCDM, the decision-maker clearly understands where most time needs to be spent on improving the underground conditions.

4.4 Recommendations for future work

Literature in Chapter 1 showed that MCDM methods had yet to be used in many different mining aspects where decision-making is essential in choosing the most suitable project. This section will recommend further studies on broadening scientific decision-making methods in the mining industry.

4.4.1 Evaluation criteria

Increase the evaluation criteria for underground ventilation and cooling projects. Many other aspects are outside the current decision-making processes due to the difficulty of adding a cost value to that aspect in order to compare with other criteria. These criteria can include projects' carbon emissions, efficiency, and accessibility, with many more criteria specific to each project and mine. Research to establish an easy and "compact" method that can be used on a mine daily to improve their decision-making abilities is recommended.

An investigation should be done to assess the use of sub-criteria to broaden the detail of the criteria considered. The possibility of some of the main criteria being broken down into sub-criteria to incorporate detail must be investigated.

4.4.2 Detailed simulations

Expand on the method to incorporate the smaller operational improvement ventilation and cooling projects during identification and ranking. During the pre-feasibility stage of the project, an in-depth simulation model will take a lot of time and energy to develop accurately, so a rapid method should be studied to add these projects during the feasibility stage.

4.4.3 Risk elaboration

A study on the manner in which health, safety, and implementation risk can be incorporated into the MCDM methods is recommended, as different projects have different risks, and a broader risk assessment can incorporate these during the decision-making process.

4.4.4 Decrease favouritism

As the MCDM method is developed to include the decision-maker's experience during the criteria weighting, it should be addressed to decrease the possibility of bias.

BIBLIOGRAPHY

- [1] J. Yunis and E. Aliakbari, "Fraser Institute Annual Survey of Mining Companies 2021," Vancouver, 2022.
- [2] H. Pley, H. Kuipers, T. Moncks, D. Scholtz, W. Bosma, and J. van Eeden, "Working together to reenergize the South African mining industry," Johannesburg, 2018.
- [3] "Environmental economic accounts compendium," Pretoria, 2017.
- [4] C. Hartnady, "South Africa's gold production and reserves," *S Afr J Sci*, vol. 105, pp. 9–10, Sep. 2009.
- [5] T. Tandon, "List of largest gold producing countries in the world 2021," *Jagranjosh*, Jan. 10, 2022. <https://www.jagranjosh.com/general-knowledge/list-of-top-gold-producers-of-the-world-1638337583-1> (accessed Apr. 03, 2022).
- [6] J. Scholtz, "Gold cost curves," *Newsletter, Minxcon Group*, 2018.
- [7] "South Africa Gold Production, 1990 – 2022," *U.S. Geological survey*, 2021. <https://www.ceicdata.com/en/indicator/south-africa/gold-production> (accessed Apr. 04, 2022).
- [8] "Gold Focus 2020," London, 2020.
- [9] S. Moolman, "2021 update: Eskom tariff increases vs inflation since 1988 (with projections to 2023)," 2021. <https://poweroptimal.com/2021-update-eskom-tariff-increases-vs-inflation-since-1988/> (accessed Apr. 02, 2022).
- [10] K. Ratshomo and R. Nembahe, "The South African energy sector report 2019," 2019.
- [11] A. Seccombe, "Gold mining most costly in South Africa," *Business day*, Jan. 26, 2018. <https://www.businesslive.co.za/bd/companies/mining/2018-01-26-gold-mining-most-costly-in-south-africa/> (accessed Apr. 03, 2022).
- [12] "The 10 deepest mines in the world," Mar. 14, 2020. <http://www.themagazine.ca/the-10-deepest-mines-in-the-world/> (accessed Apr. 02, 2022).
- [13] L. Dong, X. Tong, X. Li, J. Zhou, S. Wang, and B. Liu, "Some developments and new insights of environmental problems and deep mining strategy for cleaner production in mines," *Journal of Cleaner Production*, vol. 210. Elsevier Ltd, pp. 1562–1578, Feb. 10, 2019. doi: 10.1016/J.JCLEPRO.2018.10.291.
- [14] H. Wagner, "The management of heat flow in deep mines (Part 1)," *Geomechanik und Tunnelbau*, vol. 3, no. 5, pp. 609–621, 2010, doi: 10.1002/GEOT.201000050.

- [15] H. Wagner, "The management of heat flow in deep mines (part 2)," *Geomechanics and Tunnelling*, vol. 4, no. 2, pp. 157–163, Apr. 2011, doi: 10.1002/GEOT.201100006.
- [16] A. Habibi, R. Kramer, and A. Gillies, "Investigating the effects of heat changes in an underground mine," *Appl Therm Eng*, vol. 90, pp. 1164–1171, Jan. 2015, doi: 10.1016/J.APPLTHERMALENG.2014.12.066.
- [17] S. Roy, D. P. Mishra, · Ram, M. Bhattacharjee, and H. Agrawal, "Heat Stress in underground mines and its control measures: A systematic literature review and retrospective analysis," *Mining, Metallurgy & Exploration 2022*, vol. 1, pp. 1–27, Jan. 2022, doi: 10.1007/S42461-021-00532-6.
- [18] B. Belle and M. Biffi, "Cooling pathways for deep Australian longwall coal mines of the future," *Int J Min Sci Technol*, vol. 28, no. 6, pp. 865–875, Nov. 2018, doi: 10.1016/J.IJMST.2018.02.001.
- [19] "Mine Health and Safety Act No. 29 of 1996 and Regulations," 2018.
- [20] R. Webber, R. Franz, W. Marx, and P. Schutte, "A review of local and international heat stress indices, standards and limits with reference to ultra-deep mining," *The Journal of The South African Institute of Mining and Metallurgy*, vol. 103, no. 5, pp. 313–324, 2003.
- [21] E. De Souza, "Improving the energy efficiency of mine fan assemblages," *Appl Therm Eng*, vol. 90, pp. 1092–1097, Nov. 2015, doi: 10.1016/J.APPLTHERMALENG.2015.04.048.
- [22] C. Cilliers, "Benchmarking electricity use on deep-level mines," PhD, North-West University, Potchefstroom, South Africa, 2015. Accessed: Jun. 28, 2021. [Online]. Available: https://repository.nwu.ac.za/bitstream/handle/10394/19154/Cilliers_C_2016.pdf?sequence=1
- [23] L. Mackay, S. Bluhm, and J. van Rensburg, "Refrigeration and cooling concepts for ultra deep platinum mining," in *The 4th International Platinum Conference, Platinum in transition 'Boom or Bust' Conference Proceedings, Sun City, South Africa, 2010.*, 2010, pp. 285–292.
- [24] J. du Plessis, *Ventilation and occupational environment engineering in mines*, 3rd ed. Johannesburg: Mine Ventilation Society of South Africa, 2014.
- [25] A. J. Nel, J. Vosloo, and M. Mathews, "Evaluating complex mine ventilation operational changes through simulations," *Journal of Energy in Southern Africa*, vol. 29, no. 3, pp. 22–32, Aug. 2018, doi: 10.17159/2413-3051/2018/V29I3A4445.
- [26] S. Bluhm, F. von Glehn, and H. Smit, "Important basics of mine ventilation and cooling planning," *Journal of the mine ventilation society of South Africa*, vol. 57, no. 1, pp. 15–24, 2004.

- [27] M. Schluse, L. Atorf, and J. Rossmann, "Experimentable digital twins for model-based systems engineering and simulation-based development," in *11th Annual IEEE International Systems Conference, SysCon 2017 - Proceedings*, May 2017. doi: 10.1109/SYSCON.2017.7934796.
- [28] I. Mathews, J. van Laar, D. Arndt, J. Vosloo, and G. Seetal, "Integrated dynamic simulation method for deep-level mine cooling system planning," in *SAIIE32*, 2021, pp. 669–686.
- [29] G. Danko, D. Bahrami, and C. Stewart, "Applications and verification of a computational energy dynamics model for mine climate simulations," *Int J Min Sci Technol*, vol. 30, no. 4, pp. 483–493, Jul. 2020, doi: 10.1016/J.IJMST.2020.03.019.
- [30] E. Acuna, R. Alvarez, and S. Hardcastle, "A theoretical comparison of ventilation on demand strategies for auxiliary mine ventilation systems," in *10th International Mine Ventilation Congress, IMVC2014*, 2014.
- [31] G. Baiden, Y. Bissiri, S. Hardcastle, and C. Kocsis, "Justification of 'on-demand' ventilation systems by means of simulation techniques," in *Application of Computers and Operations Research in the Mineral Industry - Proc. of the 32nd Int. Symposium on the Application of Computers and Operations Research in the Mineral Industry, APCOM 2005*, A.A. Balkema Publishers, 2005, pp. 457–462. doi: 10.1201/9781439833407.ch61.
- [32] M. Bascompta, A. Castañón, L. Sanmiquel, and J. Oliva, "Heat flow assessment in an underground mine: An approach to improve the environmental conditions," *Dyna (Medellin)*, vol. 83, no. 197, p. 174, Jun. 2016, doi: 10.15446/DYNA.V83N197.52182.
- [33] J. Cheng *et al.*, "Comprehensive and integrated mine ventilation consultation model - CIMVCM," *Tunnelling and Underground Space Technology*, vol. 45, pp. 166–180, Dec. 2014, doi: 10.1016/J.TRUST.2014.09.004.
- [34] E. De Souza, "Optimization of complex mine ventilation systems with computer network modelling," *IFAC Proceedings Volumes*, vol. 40, no. 11, pp. 323–329, Jan. 2007, doi: 10.3182/20070821-3-CA-2919.00049.
- [35] J. du Plessis, W. Marx, and C. Nell, "Efficient use of energy in the ventilation and cooling of mines," in *A Southern African silver anniversary meeting*, Dec. 2014, vol. 114, no. 12.
- [36] J. du Plessis, D. Hoffman, W. Marx, and R. van der Westhuizen, "Optimising ventilation and cooling systems for an operating mine using network simulation models," 2013.
- [37] R. Krog, R. Grau, T. Mucho, and S. Robertson, "Ventilation planning layouts for large opening mines.," in *Proceedings of the society for mining, metallurgy, and exploration annual meeting*, 2004, pp. 1–9.

- [38] P. Mare, "Novel simulations for energy management of mine cooling systems," PhD, North-West University, Potchefstroom, South Africa, 2016.
- [39] A. Sasmito, E. Birgersson, H. Ly, and A. Mujumdar, "Some approaches to improve ventilation system in underground coal mines environment – A computational fluid dynamic study," *Tunnelling and Underground Space Technology*, vol. 34, pp. 82–95, Feb. 2013, doi: 10.1016/J.TRUST.2012.09.006.
- [40] T. Peskens, M. Buxton, M. Rinne, and I. Vervoort, "Underground mining method selection and preliminary techno-economic mine design for the Wombat orebody," Masters, Delft University of Technology, 2013. Accessed: Mar. 04, 2022. [Online]. Available: <https://repository.tudelft.nl/islandora/object/uuid%3A77005b40-e79f-479f-aa68-5a197a310c56>
- [41] S. Gupta and U. Kumar, "An analytical hierarchy process (AHP)-guided decision model for underground mining method selection," vol. 26, no. 4, pp. 324–336, Dec. 2012, doi: 10.1080/17480930.2011.622480.
- [42] M. Kizil, S. Abdalla, and I. Canbulat, "Underground coal mine layout selection using analytical hierarchy process," *Mining Technology*, vol. 123, no. 1, pp. 20–29, 2014, doi: 10.1179/1743286313Y.0000000053.
- [43] O. Dayo-Olupona, B. Genc, and M. Onifade, "Technology adoption in mining: A multi-criteria method to select emerging technology in surface mines," *Resources Policy*, vol. 69, p. 101879, Dec. 2020, doi: 10.1016/J.RESOURPOL.2020.101879.
- [44] M. Yavuz, "Equipment selection based on the AHP and Yager's method," *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 115, no. 5, pp. 425–433, May 2015, doi: 10.17159/2411-9717/2015/V115N5A10.
- [45] U. Issa, F. Saeed, Y. Miky, M. Alqurashi, and E. Osman, "Hybrid AHP-Fuzzy TOPSIS approach for selecting deep excavation support system," *Buildings*, vol. 12, no. 3, p. 295, Mar. 2022, doi: 10.3390/BUILDINGS12030295.
- [46] F. Namin, K. Shahriar, A. Bascetin, and S. Ghodssypour, "Practical applications from decision-making techniques for selection of suitable mining method in Iran," *Gospodarka Surowcami Mineralnymi-mineral Resources Management*, vol. 25, no. 3, pp. 57–77, 2009.
- [47] C. Stojanovic, D. Bogdanovic, and S. Urosevic, "Selection of the optimal technology for surface mining by multi-criteria analysis," *Kuwait Journal of Science*, vol. 42, no. 3, pp. 170–190, 2015.

- [48] R. Lin, S. Lu, A. Yang, W. Shen, and J. Ren, "Multi-criteria sustainability assessment and decision-making framework for hydrogen pathways prioritization: An extended ELECTRE method under hybrid information," *Int J Hydrogen Energy*, vol. 46, no. 24, pp. 13430–13445, Apr. 2021, doi: 10.1016/J.IJHYDENE.2021.01.018.
- [49] Q. Jia, H. Hu, and J. Yu, "The model construction in airport renewable energy system scale planning based in Multi-Criteria Decision Making," *Energy Reports*, vol. 7, pp. 92–98, Nov. 2021, doi: 10.1016/J.EGYR.2021.08.068.
- [50] J. Gao, H. Men, F. Guo, P. Liang, and Y. Fan, "A multi-criteria decision-making framework for the location of photovoltaic power coupling hydrogen storage projects," *J Energy Storage*, vol. 44, p. 103469, Dec. 2021, doi: 10.1016/J.EST.2021.103469.
- [51] C. El-Bayeh, K. Alzaareer, B. Brahmi, M. Zellagui, and U. Eicker, "An original multi-criteria decision-making algorithm for solar panels selection in buildings," *Energy*, vol. 217, p. 119396, Feb. 2021, doi: 10.1016/J.ENERGY.2020.119396.
- [52] L. Nhung, T. Phung, H. Nguyen, T. Le, T. Nguyen, and T. Vo, "Load shedding in microgrids with dual neural networks and AHP algorithm," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8090–8095, Feb. 2022, doi: 10.48084/ESTASR.4652.
- [53] C. Zuheros, E. Martínez-Cámara, E. Herrera-Viedma, and F. Herrera, "Sentiment Analysis based Multi-Person Multi-criteria Decision Making methodology using natural language processing and deep learning for smarter decision aid. Case study of restaurant choice using TripAdvisor reviews," *Information Fusion*, vol. 68, pp. 22–36, Apr. 2021, doi: 10.1016/J.INFFUS.2020.10.019.
- [54] N. Chowdhury, M. Kabir, M. Rahman, and S. Islam, "Machine learning for detecting COVID-19 from cough sounds: An ensemble-based MCDM method," *Comput Biol Med*, vol. 145, Jun. 2022, doi: 10.1016/J.COMPBIOMED.2022.105405.
- [55] P. Jorissen, K. Moons, L. Pintelon, D. De Ridder, and W. Everaerts, "Identification of multi-stakeholder value in prostate cancer treatment by application of Multi-Criteria Decision Making (MCDM)," *European Urology Supplements*, vol. 18, no. 1, pp. e2184–e2185, Mar. 2019, doi: 10.1016/S1569-9056(19)31578-7.
- [56] S. Zolfani, M. Aghdaie, A. Derakhti, E. Zavadskas, and M. Varzandeh, "Decision making on business issues with foresight perspective; an application of new hybrid MCDM model in shopping mall locating," *Expert Syst Appl*, vol. 40, no. 17, pp. 7111–7121, Dec. 2013, doi: 10.1016/J.ESWA.2013.06.040.

- [57] M. Yasmin, E. Tatoglu, H. S. Kilic, S. Zaim, and D. Delen, "Big data analytics capabilities and firm performance: An integrated MCDM approach," *J Bus Res*, vol. 114, pp. 1–15, Jun. 2020, doi: 10.1016/J.JBUSRES.2020.03.028.
- [58] S. Vijayakumar, P. Suresh, K. Sasikumar, K. Pasupathi, T. Yuvaraj, and D. Velmurugan, "Evaluation and selection of projects using hybrid MCDM technique under fuzzy environment based on financial factors," *Mater Today Proc*, Nov. 2021, doi: 10.1016/J.MATPR.2021.10.138.
- [59] L. Dimova, P. Sevastianov, and D. Sevastianov, "MCDM in a fuzzy setting: Investment projects assessment application," *Int J Prod Econ*, vol. 100, no. 1, pp. 10–29, Mar. 2006, doi: 10.1016/J.IJPE.2004.09.014.
- [60] N. Kursunoglu and M. Onder, "Selection of an appropriate fan for an underground coal mine using the Analytic Hierarchy Process," *Tunnelling and Underground Space Technology*, vol. 48, pp. 101–109, Apr. 2015, doi: 10.1016/J.TUST.2015.02.005.
- [61] P. Kluge and D. Malan, "The application of the analytical hierarchical process in complex mining engineering design problems," *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 111, pp. 847–855, 2011.
- [62] H. Nourali, S. Nourali, M. Ataei, and N. Imanipour, "A hierarchical preference voting system for mining method selection problem," *Archives of Mining Sciences*, vol. 57, no. 4, pp. 1057–1070, Dec. 2012, doi: 10.2478/V10267-012-0070-X.
- [63] F. Sitorus, J. Cilliers, and P. Brito-Parada, "Multi-criteria decision making for the choice problem in mining and mineral processing: Applications and trends," *Expert Syst Appl*, vol. 121, pp. 393–417, May 2019, doi: 10.1016/J.ESWA.2018.12.001.
- [64] C. Kocsis, S. Hardcastle, and R. Hall, "Benefit of using mine process simulators to design a 'life-cycle' mine ventilation system," *Transactions of the Institution of Mining and Metallurgy*, vol. 316, pp. 1–7, Jan. 2004, Accessed: Feb. 17, 2021. [Online]. Available: https://www.researchgate.net/publication/318796132_Benefit_of_using_mine_process_simulators_to_design_a_life-cycle_mine_ventilation_system
- [65] P. Spanidis, C. Roumpos, and F. Pavlidakis, "A multi-criteria approach for the evaluation of low risk restoration projects in continuous surface lignite mines," *Energies 2020, Vol. 13, Page 2179*, vol. 13, no. 9, p. 2179, May 2020, doi: 10.3390/EN13092179.
- [66] M. Ataei, M. Jamshidi, F. Sereshki, and S. Jalali, "Mining method selection by AHP approach," *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 108, no. 12, pp. 741–749, Dec. 2008.

- [67] C. Musingwini and R. Minnitt, "Ranking the efficiency of selected platinum mining methods using the analytic hierarchy process (AHP)," in *Third International Platinum Conference 'Platinum in Transformation,'* Sep. 2008, pp. 319–326.
- [68] J. Jamshidi, M. Ataei, F. Sereshki, and M. Seyed, "The Application of AHP Approach to Selection of Optimum Underground Mining Method, Case Study: Jajarm Bauxite Mine (Iran)," *Journal of Archives of Mining Sciences*, vol. 54, pp. 103–117, 2009.
- [69] P. Dey and E. Ramcharan, "Analytic hierarchy process helps select site for limestone quarry expansion in Barbados," *J Environ Manage*, vol. 88, no. 4, pp. 1384–1395, Sep. 2008, doi: 10.1016/J.JENVMAN.2007.07.011.
- [70] E. De Souza, "Application of ventilation management programs for improved mine safety," *Int J Min Sci Technol*, vol. 27, no. 4, pp. 647–650, 2017, doi: <https://doi.org/10.1016/J.IJMST.2017.05.018>.
- [71] I. Mathews, E. Mathews, J. van Laar, W. Hamer, and M. Kleingeld, "A simulation-based prediction model for coal-fired power plant condenser maintenance," *Appl Therm Eng*, vol. 174, pp. 1–10, 2020, doi: 10.1016.115294.
- [72] B. Friedenstein, C. Cilliers, and J. van Rensburg, "Simulating operational improvements on mine compressed air systems," *South African Journal of Industrial Engineering*, vol. 29, no. 3, pp. 69–81, 2018, doi: 10.7166/29-3-2049.
- [73] S. Alpay and M. Yavuz, "Underground mining method selection by decision making tools," *Tunnelling and Underground Space Technology*, vol. 24, no. 2, pp. 173–184, Mar. 2009, doi: 10.1016/J.TUST.2008.07.003.
- [74] M. Ali and J. Kim, "Selection mining methods via multiple criteria decision analysis using TOPSIS and modification of the UBC method," *Journal of Sustainable Mining*, vol. 20, no. 2, pp. 49–55, 2021, doi: 10.46873/2300-3960.1054.
- [75] S. Alpay and M. Yavuz, "A decision support system for underground mining method selection," in *New Trends in Applied Artificial Intelligence*, 2007, vol. 4570 LNAI, pp. 334–343.
- [76] J. Amorocho and T. Hartmann, "A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods," *Journal of Building Engineering*, vol. 53, p. 104596, Aug. 2022, doi: 10.1016/J.JOBE.2022.104596.
- [77] E. Asr, M. Hayaty, R. Rafiee, M. Ataie, and S. Jalali, "Selection of optimum tunnel support system using aggregated ranking of SAW, TOPSIS and LA methods," *International Journal of Applied Operational Research*, vol. 5, no. 4, pp. 49–63, 2015.

- [78] M. Bitarafan and M. Ataei, "Mining method selection by multiple criteria decision making tools," *The Journal of The South African Institute of Mining and Metallurgy*, vol. 109, no. 9, pp. 493–498, Oct. 2004, doi: 10.10520/AJA0038223X_2888.
- [79] D. Bogdanovic, D. Nikolic, and I. Ilic, "Mining method selection by integrated AHP and PROMETHEE method," *An Acad Bras Cienc*, vol. 84, no. 1, pp. 219–233, Mar. 2012, doi: 10.1590/S0001-37652012000100023.
- [80] B. Balusa and J. Singam, "Underground mining method selection using WPM and PROMETHEE," *Journal of The Institution of Engineers (India): Series D*, vol. 99, no. 1, pp. 165–171, Apr. 2018, doi: 10.1007/S40033-017-0137-0/TABLES/12.
- [81] A. Ebrahimabadi, "A Fuzzy AHP Approach to Select the Proper Roadheader in Tabas Coal Mine Project of Iran," Islamic Azad University, Qaemshahr, 2014.
- [82] A. Ghazikalayeh, A. Ebrahimabadi, and I. Alavi, "Selecting proper mining method using Fuzzy AHP approach (Case study: Qaleh-Zari Copper Mine of Iran)," *Journal of Applied Science and Agriculture*, vol. 9, no. 1, pp. 1–10, Jan. 2014.
- [83] M. Hayati, M. Hayati, R. Rajabzadeh, and M. Darabi, "Determination of optimal block size in Angouran Mine Using VIKOR method," *Journal of material environmental science*, vol. 6, no. 11, pp. 3236–33244, 2015, doi: 10.1.1.703.9386.
- [84] M. Hudej, S. Vujic, M. Radosavlevic, and S. Ilic, "Multi-variable selection of the main mine shaft location," *Journal of Mining Science*, vol. 49, no. 6, pp. 950–954, May 2013, doi: 10.1134/S1062739149060154.
- [85] M. Iphar and S. Alpay, "A mobile application based on multi-criteria decision-making methods for underground mining method selection," *Int J Min Reclam Environ*, vol. 33, no. 7, pp. 480–504, Oct. 2018, doi: 10.1080/17480930.2018.1467655.
- [86] G. Ibishi, M. Yavuz, and M. Genis, "Underground mining method assessment using decision-making techniques in a fuzzy environment case study, Trepça mine, Kosovo," *Mining of Mineral Deposits*, 2020, doi: 10.33271/MINNING14.03.134.
- [87] M. Javanshirgiv and M. Safari, "The selection of an underground mining method using the fuzzy topsis method: A case study in the Kamar Mahdi II fluorine mine," *Mining Science*, vol. 24, pp. 161–181, Aug. 2017, doi: 10.5277/MS172410.
- [88] E. Kabwe, "Optimal mining method selection for Nchanga's Upper Orebody using analytic hierarchy process and Yager's method," *Mining Technology*, vol. 126, no. 3, pp. 151–162, Jul. 2017, doi: 10.1080/14749009.2016.1274840.

- [89] M. Kizil, S. Abdalla, and I. Canbulat, "Development of a method for layout selection using analytical hierarchy process," *Mining Technology*, vol. 123, no. 1, pp. 20–29, 2014.
- [90] A. Karadogan, A. Kahriman, and U. Ozer, "Application of fuzzy set theory in the selection of underground mining method," *Journal of The South African Institute of Mining and Metallurgy*, vol. 108, no. 2, pp. 73–79, 2008.
- [91] V. Kazakidis, Z. Mayer, and M. Scoble, "Decision making using the analytic hierarchy process in mining engineering," *Mining Technology*, vol. 113, no. 1, 2013, doi: 10.1179/037178404225004274.
- [92] P. Mare, "Improved implementation strategies to sustain energy saving measures on mine cooling system," Masters, University of North-West, Potchefstroom, South Africa, 2015. doi: 10.1016/S0007-0785(45)80017-0.
- [93] F. Owusu-Mensah and C. Musingwini, "Evaluation of ore transport options from Kwesi Mensah Shaft to the mill at the Obuasi mine," *Int J Min Reclam Environ*, vol. 25, no. 2, pp. 109–125, Jun. 2011, doi: 10.1080/17480930.2010.538988.
- [94] M. Özfirat, "A fuzzy method for selecting underground coal mining method considering mechanization criteria," *Journal of Mining Science*, vol. 48, no. 3, pp. 533–544, Nov. 2012, doi: 10.1134/S1062739148030173.
- [95] C. Wang, S. Yang, C. Jiang, G. Wu, and Q. Liu, "Monte Carlo analytic hierarchy process for selection of the longwall mining method in thin coal seams," *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 119, pp. 1005–1012, 2019, doi: 10.17159/2411-9717/17/375/2020.
- [96] C. Wang and S. Tu, "Selection of an appropriate mechanized mining technical process for thin coal seam mining," *Math Probl Eng*, vol. 2015, 2015, doi: 10.1155/2015/893232.
- [97] M. Yavuz and S. Alpay, "Underground mining technique selection by multicriterion optimization methods," *Journal of Mining Science*, vol. 44, no. 4, pp. 391–401, Jul. 2008, doi: 10.1007/S10913-008-0043-9.
- [98] M. Yavuz, "The application of the analytic hierarchy process (AHP) and Yager's method in underground mining method selection problem," *Int J Min Reclam Environ*, vol. 29, no. 6, pp. 453–475, Nov. 2014, doi: 10.1080/17480930.2014.895218.
- [99] M. Yavuz, M. Iphar, and G. Once, "The optimum support design selection by using AHP method for the main haulage road in WLC Tuncbilek colliery," *Tunnelling and Underground Space Technology*, vol. 23, no. 2, pp. 111–119, Mar. 2008, doi: 10.1016/J.TUST.2007.02.001.

- [100] M. Yetkin and M. Özfirat, "Selection of thick coal seam mining method using analytic hierarchy process," *Journal of Engineering and Technology for Industrial Applications*, vol. 5, no. 20, pp. 6–11, 2019, doi: 10.5935/2447-0228.20190071.
- [101] P. Gulum, E. Ayyildiz, and A. Taskin Gumus, "A two level interval valued neutrosophic AHP integrated TOPSIS methodology for post-earthquake fire risk assessment: An application for Istanbul," *International Journal of Disaster Risk Reduction*, vol. 61, p. 102330, Jul. 2021, doi: 10.1016/J.IJDRR.2021.102330.
- [102] A. Nel, "Mine ventilation characterisation through simulations," PhD, North-West University, 2018.
- [103] R. Fair, J. van Laar, K. Nell, D. Nell, and E. Mathews, "Simulating the sensitivity of underground ventilation networks to fluctuating ambient conditions," *South African Journal of Industrial Engineering*, vol. 32, no. 3, pp. 42–51, 2021, doi: 10.7166/32-3-2616.
- [104] S. Teegavarapu, J. Summers, and G. Mocko, "Case study method for design research: A justification," in *20th International Conference on Design Theory and Methodology; Second International Conference on Micro- and Nanosystems*, 2008, pp. 495–503. doi: 10.1115/DETC2008-49980.
- [105] D. Nell, "Practical determination of heat loads for existing deep level gold mines," North-West University, 2019.
- [106] K. Wallace, B. Prosser, and J. Stinnette, "The practice of mine ventilation engineering," *Int J Min Sci Technol*, vol. 25, no. 2, pp. 165–169, Mar. 2015, doi: 10.1016/J.IJMST.2015.02.001.
- [107] R. Clarke and E. de Souza, "Life-of-mine ventilation planning at Diavik," *CIM Journal*, vol. 9, no. 3, pp. 121–126, Aug. 2018, doi: 10.15834/CIMJ.2018.12.
- [108] J. Stinnette, E. de Souza, and R. Buchan, "Establishing total airflow requirements for underground metal/non-metal mines for tier IV diesel equipment," Masters, Queen's University, Ontario, 2013. Accessed: Feb. 17, 2021. [Online]. Available: <https://www.mvsengineering.com/files/Publications/wmc2013Paper694.pdf>
- [109] C. Kocsis, R. Hall, and S. Hardcastle, "The integration of mine simulation and ventilation to develop a 'Life-cycle' mine ventilation system," in *Application of Computers and Operations Research in the Minerals Industries*, 2003.
- [110] M. Mcpherson, *Subsurface Ventilation Engineering*, 2nd ed. Nottingham: Mine Ventilation Services, 2015. [Online]. Available: https://www.mvsengineering.com/files/Subsurface-Book/MVS-SVE_Chapter00.pdf

- [111] M. Biffi and D. Stanton, "Cooling power for a new age," in *Third International Platinum Conference 'Platinum in Transformation,'* 2008, pp. 239–247.
- [112] A. Donoghue, M. Sinclair, and G. Bates, "Heat exhaustion in a deep underground metalliferous mine," *Occup Environ Med*, vol. 57, pp. 165–174, 2000, doi: 10.1136/OEM.57.3.165.
- [113] S. Maloney and C. Forbes, "What effect will a few degrees of climate change have on human heat balance? Implications for human activity," *Int J Biometeorol*, vol. 55, no. 2, pp. 147–160, Mar. 2011, doi: 10.1007/S00484-010-0320-6/FIGURES/4.
- [114] F. C. Bernard and L. J. Grobler, "Baseline service level adjustment methodologies for energy efficiency projects on compressed air systems in the mining industry," in *2012 Proceedings of the 9th Industrial and Commercial Use of Energy Conference*, 2012, pp. 1–8.
- [115] S. Bluhm, F. von Glehn, W. Marx, and M. Biffi, "VUMA mine ventilation software," *Journal of mine ventilation society of South Africa*, vol. 54, no. 3, pp. 65–72, 2001.
- [116] M. Morar, S. Radu, D. Cioclea, and I. Gherghe, "Use of IT equipment and specialized programs for solving ventilation networks," *Qual.- Access to Success*, vol. 18, no. S1, pp. 121–126, 2017.
- [117] G. Ding, "Recent developments in simulation techniques for vapour-compression refrigeration systems," *International Journal of Refrigeration*, vol. 30, no. 7, pp. 1119–1133, Nov. 2007, doi: 10.1016/J.IJREFRIG.2007.02.001.
- [118] F. Wei, Z. Fangping, and L. Huiqing, "The use of 3D simulation system in mine ventilation management," *Procedia Eng*, vol. 26, pp. 1370–1379, Jan. 2011, doi: 10.1016/J.PROENG.2011.11.2313.
- [119] G. du Plessis, D. Arndt, and E. Mathews, "The development and integrated simulation of a variable water flow energy saving strategy for deep-mine cooling systems," *Sustainable Energy Technologies and Assessments*, vol. 10, pp. 71–78, Jun. 2015, doi: 10.1016/J.SETA.2015.03.002.
- [120] J. du Plessis and M. van der Bank, "In-stope dust control at Beatrix Gold mine," in *Cost Reduction and Milestone Achievements*, 2015.
- [121] M. Karsten and L. Mackay, "Underground environmental challenges in deep platinum mining and some suggested solutions," in *A catalyst for change*, 2012, pp. 177–192.
- [122] I. Jiskani, B. Moreno-Cabezali, A. Ur Rehman, J. Fernandez-Crehuet, and S. Uddin, "Implications to secure mineral supply for clean energy technologies for developing countries:

- A fuzzy based risk analysis for mining projects," *J Clean Prod*, vol. 358, p. 132055, Jul. 2022, doi: 10.1016/J.JCLEPRO.2022.132055.
- [123] D. del Castillo, "Minimising the electrical power usage of large refrigeration installations on South African mines," *Journal of the mine ventilation society of South Africa*, vol. 65, no. 4, pp. 6–13, 2012.
- [124] A. Kamyar, S. Mostafa Aminossadati, C. Leonardi, and A. Sasmito, "Current developments and challenges of underground mine ventilation and cooling methods," in *16th Coal Operators' Conference*, 2016, pp. 10–12.
- [125] H. Dehghani and M. Ataee-pour, "Determination of the effect of operating cost uncertainty on mining project evaluation," *Resources Policy*, vol. 37, no. 1, pp. 109–117, Mar. 2012, doi: 10.1016/J.RESOURPOL.2011.11.001.
- [126] A. J. Nel, D. Arndt, J. Vosloo, and M. Mathews, "Achieving energy efficiency with medium voltage variable speed drives for ventilation-on-demand in South African mines," *J Clean Prod*, vol. 232, pp. 379–390, 2019, doi: 10.1016/J.JCLEPRO.2019.05.376.
- [127] R. Larry Grayson, H. Kinilakodi, and V. Kecojevic, "Pilot sample risk analysis for underground coal mine fires and explosions using MSHA citation data," *Saf Sci*, vol. 47, no. 10, pp. 1371–1378, Dec. 2009, doi: 10.1016/J.SSCI.2009.03.004.
- [128] I. Jiskani, Q. Cai, W. Zhou, and X. Lu, "Assessment of risks impeding sustainable mining in Pakistan using fuzzy synthetic evaluation," *Resources Policy*, vol. 69, p. 101820, Dec. 2020, doi: 10.1016/J.RESOURPOL.2020.101820.
- [129] N. Duijm, "Recommendations on the use and design of risk matrices," *Saf Sci*, vol. 76, pp. 21–31, Jul. 2015, doi: 10.1016/J.SSCI.2015.02.014.
- [130] P. Dey, "Managing project risk using combined analytic hierarchy process and risk map," *Appl Soft Comput*, vol. 10, no. 4, pp. 990–1000, Sep. 2010, doi: 10.1016/J.ASOC.2010.03.010.
- [131] S. Ibarra-Gutiérrez, J. Bouchard, M. Laflamme, and K. Fytas, "Project economics of lithium mines in Quebec: A critical review," *Extr Ind Soc*, vol. 8, no. 4, p. 100984, Dec. 2021, doi: 10.1016/J.EXIS.2021.100984.
- [132] R. Bullock, *SME Mining Engineering Handbook*, 3rd ed. Littleton, CO: Society for Mining, Metallurgy & Exploration, 2011.
- [133] M. Mohutsiwa and C. Musingwini, "Parametric estimation of capital costs for establishing a coal mine: South Africa case study," *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 115, pp. 789–797, 2015, doi: 10.17159/2411-9717/2015/V115N8A17.
- [134] T. Saaty, *The Analytic Hierarchy Process*. Pittsburgh: McGraw-Hill, 1980.

- [135] R. Atkinson, "Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria," *International Journal of Project Management*, vol. 17, no. 6, pp. 337–342, Dec. 1999, doi: 10.1016/S0263-7863(98)00069-6.
- [136] S. Gunathilaka and N. Amarasingha, "Using social and economic factors for ranking pavement maintenance and rehabilitation projects," *Asian Transport Studies*, vol. 6, p. 100026, Jan. 2020, doi: 10.1016/J.EASTSJ.2020.100026.
- [137] W. Liang, G. Zhao, and H. Wu, "Evaluating investment risks of metallic mines using an extended TOPSIS method with linguistic neutrosophic numbers," *Symmetry* 2017, Vol. 9, Page 149, vol. 9, no. 8, p. 149, Aug. 2017, doi: 10.3390/SYM9080149.
- [138] M. Kun, Ş. Topaloğlu, T. Malli, M. Kun, Ş. Topaloğlu, and T. Malli, "Evaluation of wheel loaders in open pit marble quarrying by using the AHP and Topsis approaches," *Archives of Mining Sciences*, vol. 58, no. 1, pp. 255–267, Mar. 2013, doi: 10.2478/AMSC-2013-0018.
- [139] T. Saaty, "Decision making with the Analytic Hierarchy Process," *International Journal Services Sciences*, vol. 1, no. 1, 2008, doi: 10.1504/IJSSCI.2008.017590.
- [140] B. Balusa and A. Gorai, "Sensitivity analysis of fuzzy-analytic hierarchical process (FAHP) decision-making model in selection of underground metal mining method," *Journal of Sustainable Mining*, vol. 18, no. 1, pp. 8–17, Feb. 2019, doi: 10.1016/J.JSM.2018.10.003.
- [141] V. Baloyi and L. Meyer, "The development of a mining method selection model through a detailed assessment of multi-criteria decision methods," *Results in Engineering*, vol. 8, p. 100172, Dec. 2020, doi: 10.1016/J.RINENG.2020.100172.
- [142] D. Olson, "Comparison of weights in TOPSIS models," *Math Comput Model*, vol. 40, no. 7–8, pp. 721–727, 2004, doi: 10.1016/J.MCM.2004.10.003.
- [143] J. Swanepoel, J. Vosloo, J. van Laar, and W. Pelser, "Prioritisation of environmental improvement projects in deep-level mine ventilation systems," *Min Metall Explor*, vol. 1, pp. 1–18, Feb. 2023, doi: 10.1007/S42461-023-00738-W.

APPENDIX A: RETURN TEMPERATURES

The return temperatures are also collected during the third phase of Step 1. These temperatures assist in developing the simulation model. Table A-1 shows the return flows and temperatures.

Table A-1: Mine's return flows and temperature

Ref.	Level	Return			
		Mass flow (kg/s)	Velocity (m/s)	Wet-bulb Temp (°C)	Dry-bulb Temp (°C)
O	272	21.4	0.7	27.2	31.0
P	273	14.9	1.7	36.3	38.2
Q	280	33.1	1.1	33.0	38.3
R	284	61.3	2.0	30.67	34.6
S	287	16.2	0.5	28.3	32.3
T	289	16.9	0.5	30.8	35.7
U	291	46.6	1.5	33.8	35.9
V	MB return	197.3	5.47	32.5	36.2

APPENDIX B: DETERMINE MODEL ACCURACY

The percentage error for the locations shown in Figure 3-8 can be seen in Table B-1. Additional values are added throughout the levels to improve the accuracy and are indicated with the letter and a roman numeral next to it.

Table B-1: Model's percentage error values

Ref.	Sub-level	Mass flow (kg/s)			Wet-bulb Temp (°C)			Dry-bulb Temp (°C)		
		Mea	Sim	%E	Mea	Sim	%E	Mea	Sim	%E
A		236.8	251.3	6.12	20.2	19.0	5.8	27.9	27.9	0.0
B		42.2	42.1	0.1	27.6	27.3	0.1	30.4	30.6	1.0
C		183.1	216.4	18.2	25.8	26.8	4.0	33.4	31.8	4.7
D		56.5	54.2	4.0	35.0	35.9	2.3	38.5	37.7	2.1
D	I (BAC in)	139.3	150.7	8.2	31.0	30.1	2.9	31.1	32.8	5.6
D	II (BAC out)	96.7	102.7	6.1	22.1	21.8	1.0	22.1	21.8	1.0
E	I	99.3	95.9	3.5	26.9	26.7	0.6	28.2	28.4	0.6
E	II	130.8	116.7	10.8	23.8	24.0	0.5	25.1	25.6	1.9
F		28.4	27.0	5.0	26.4	26.5	0.4	29.7	29.7	0.0
F	I	10.5	9.1	12.8	27.2	27.5	1.0	30.2	30.8	1.9
F	II	21.4	17.4	18.5	27.1	28.3	4.4	31.1	32.0	3.0
G		45.3	43.7	3.7	26.7	27.6	3.6	29.8	29.6	0.7
G	I	12.6	15.8	24.7	28.6	28.5	0.1	32.4	32.4	0.0
H		23.4	22.5	4.0	28.8	28.8	0.0	31.5	31.3	0.7
I		12.1	11.4	6.0	29.7	29.3	1.3	30.5	31.0	1.4
J		147.7	152.6	3.9	28.8	27.7	4.0	30.0	30.5	1.6
K		37.0	30.1	18.6	29.5	29.3	0.6	31.8	31.7	0.1
L		53.3	49.7	6.7	26.0	30.9	18.7	32.3	33.6	3.9
M		12.5	16.2	29.4	28.4	29.1	2.6	31.8	31.0	2.5
M	I	26.8	29.0	8.3	28.4	28.6	0.7	28.9	29.6	2.4
N		60.7	62.2	2.4	29.1	31.4	7.9	35.4	34.1	3.8
N	I	32.2	35.6	10.8	30.7	31.7	3.3	33.6	34.1	1.5
O		16.1	15.0	7.3	29.8	31.2	4.6	35.0	35.2	0.4
P		1.1	1.2	4.1	36.3	36.4	0.1	38.2	38.4	0.3
P	II	10.4	10.5	0.5	33.8	34.1	0.8	33.5	42.2	26.1
Q		33.1	32.6	1.5	33.0	35.2	6.6	38.3	37.9	0.9
Q	I	14.7	17.7	20.8	34.1	33.7	1.0	38.2	36.8	3.7
R		61.3	53.3	13.0	30.7	30.1	1.8	34.6	33.3	3.9
S		16.2	15.6	3.6	28.3	31.6	11.7	32.3	34.0	5.3
T		16.9	16.2	4.3	30.8	31.2	1.3	35.7	35.9	0.5
U		46.6	51.5	10.5	33.8	36.0	6.4	35.9	34.3	4.6
V		197.3	212.6	6.7	32.5	35.0	7.7	36.2	36.9	1.9

Mea = measured value, Sim = simulated results

APPENDIX C: PROJECT DETAIL

The projects listed in Table 3-3 and Table 3-4 are explained in more detail in this appendix. Table C-1 gives more detail regarding the ventilation-orientated projects, while Table C-2 gives more information regarding the cooling-orientated projects.

Table C-1: Detail ventilation projects description

Symbol	Project	Detail description
A ₁	Additional/ new shaft	Develop a new shaft that will serve as an intake and return directly to the mining block. The downcast (intake air) will link up with the 291 level, while the return RAW will connect with the 276 RAW. Implementing this new shaft will remove the dependence on the old RAW and intake. The current access shaft is located 6 km away from the mining block, affecting future extensions.
A ₂	Cross-over	The development of a cross-over on 52 level will enable the mine to make a section of the RAW, which is one haulage, into two haulages. Currently, it is one RAW and one intake haulage from 2#. The cross-over is an option because the RAW is degrading, and the RAW is linked to the old working areas.
A ₃	Condenser pond 5	The refrigeration circuit's heat exchange happens at the condenser ponds situated in the RAW. Four booster fans extract the air out of the mine and over the condenser ponds. The projects are to add an extra booster fan and condenser pond to the system, add more return capacity and increase the heat exchange.
A ₄	Additional fans in the RAW	The mining block consists of many fans at each level and places the mining block under a negative pressure. The hot air recirculates through the mine if an opening is linked to the RAW. Installing two large fans will place the mining block under a positive pressure, and the quantity of air removed from the block can increase.
A ₅	New straight RAW to 1#	The RAW at the back of the condenser ponds splits into three levels employing boreholes that are inaccessible and reason to believe it is not in good condition. The idea is to develop a straight haulage to 1#. This will bypass the current system and shorten the distance of air travelling. The new haulage will be shorter with less friction.

A ₆	Rehabilitate the current RAW	The RAW between 1# and 5# is a section that can be accessed and is in bad condition with FOG and restrictions. The project will be to clean the FOG and support the roof.
A ₇	Additional RAW to 5#	The condition of the RAW behind the condenser pond is not accessible, and a particular part of the RAW is through old working areas and declines. The project involves developing a new haulage from the condenser ponds to the return shaft, 5#. The project will reduce the resistance, and the condition will be known.
A ₈	Additional intake and return haulage	This project entails developing an extra intake haulage and return haulage at the sections that consist only of one haulage. This will increase the intake and return haulage capabilities while decreasing the risk with more than one haulage.

Table C-2: Detail cooling projects descriptions

Symbol	Project	Detail description
A ₉	Underground refrigeration	The cooling circuit consists of nine refrigeration plants with an open location between plant 7 and plant 9. The project entails adding an additional refrigeration plant at this open area named FP8. This will add an HM20 to the lag CC2 of the refrigeration circuit. This HM20 will serve as redundancy for FP3 when maintenance is taking place.
A ₁₀	Intake air BAC (Decline)	The project wants to cool a large amount of the air coming from the surface before it gets to the 255 level BACs and mining block. This will assist in moving some of the cooling on 255 level to the mining block.
A ₁₁	Intake air BAC (1C sub-shaft)	The project wants to cool the air that goes down at 1C# because of the significant increase in air temperature from that sub-shaft. This cools the air before it reaches the 255 level BACs and mining block. More air can then be moved from 255 level to the mining block.
A ₁₂	Surface refrigeration	Most mines start their cooling with a refrigeration circuit on the surface, as seen in the hierarchy of cooling in Figure 1-6. As the mine's depth increases, the cooling moves down the mine and closer to the working area, still having surface refrigeration. The mine does not have surface cooling, and the intake air temperature is already

		high by the time it reaches the BACs on 255 level. This plan is to start already cooling the air before going underground, and this will assist in moving some of the cooling on 255 level to the mining block.
A ₁₃	Electric vehicles	The mechanised mine operates diesel machinery which forms a large part of the heat load in the mine. Changing the diesel machinery to electric vehicles will decrease the heat load from the machinery. Another reason for the proposed change is that the diesel machinery's diesel particulate matter (DPM) may be regulated in the coming years.
A ₁₄	291 Chill pond	Install a new chill pond in the mining block on 291 level. By switching off one of the chill ponds (Chill pond 2) on 255 level, the water/cooling can be moved closer to the working areas. This will entail developing a new haulage on 291 level, piping the water from 289 chill pond, and building a new chill pond. The chill pond will also assist with future development.

APPENDIX D: QUANTIFY IMPACT DETAIL

The changes made to the baseline model to simulate the project will be discussed and illustrated, where possible followed by the air cooling power values for each level.

Changes to baseline model

Table D-1 shows the changes made to “implement” the ventilation projects, while Table D-2 shows the changes made to “implement” the cooling project.

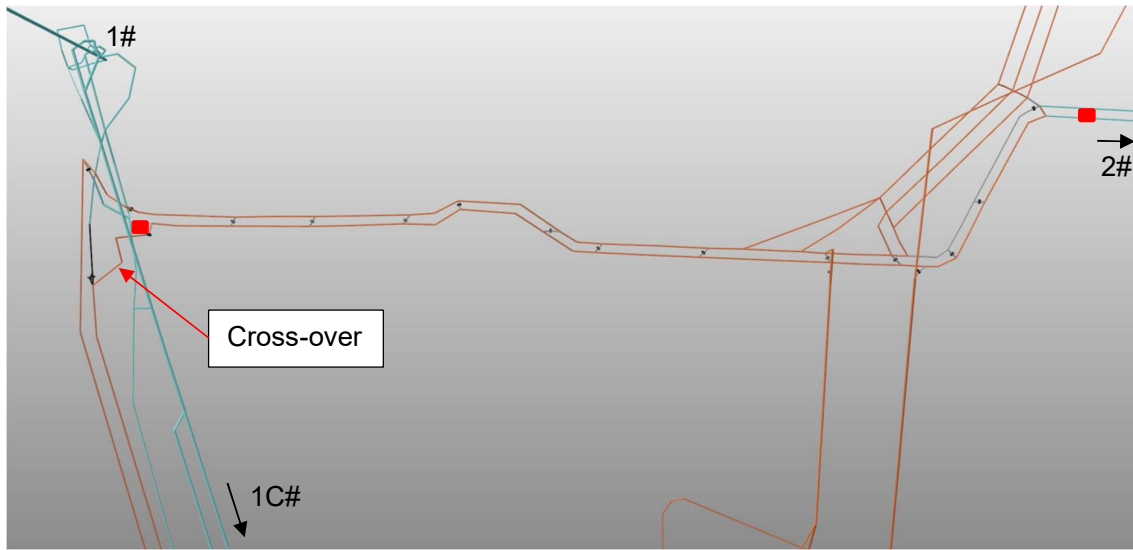
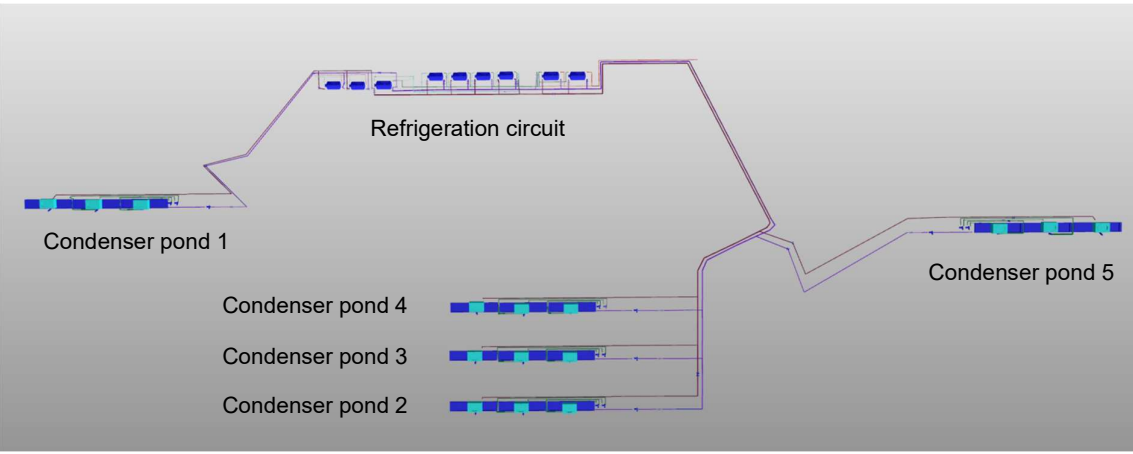
Table D-1: Changes to the baseline simulation model per project - Ventilation

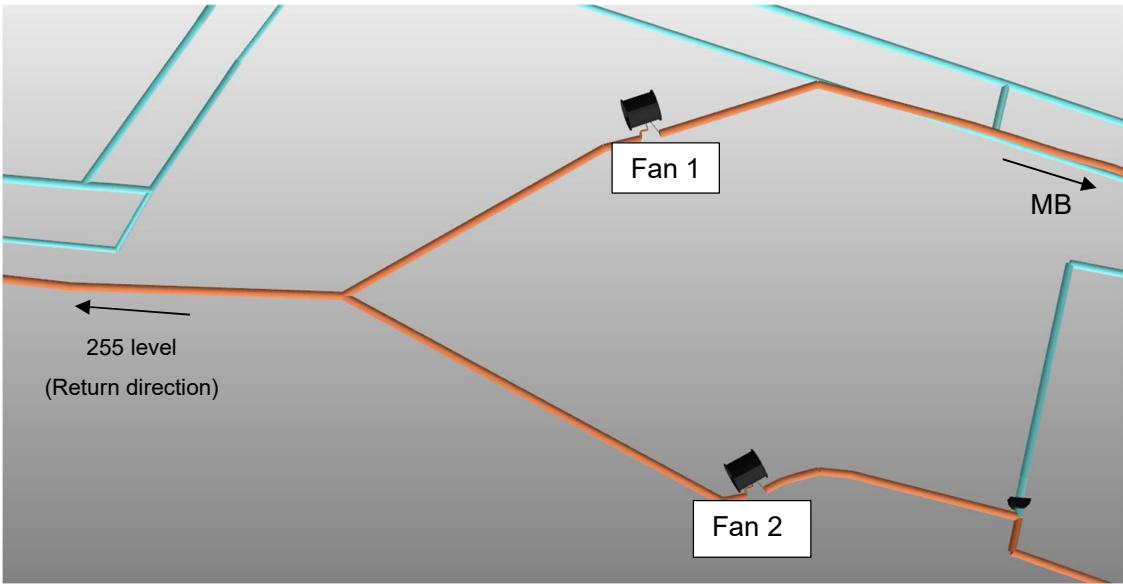
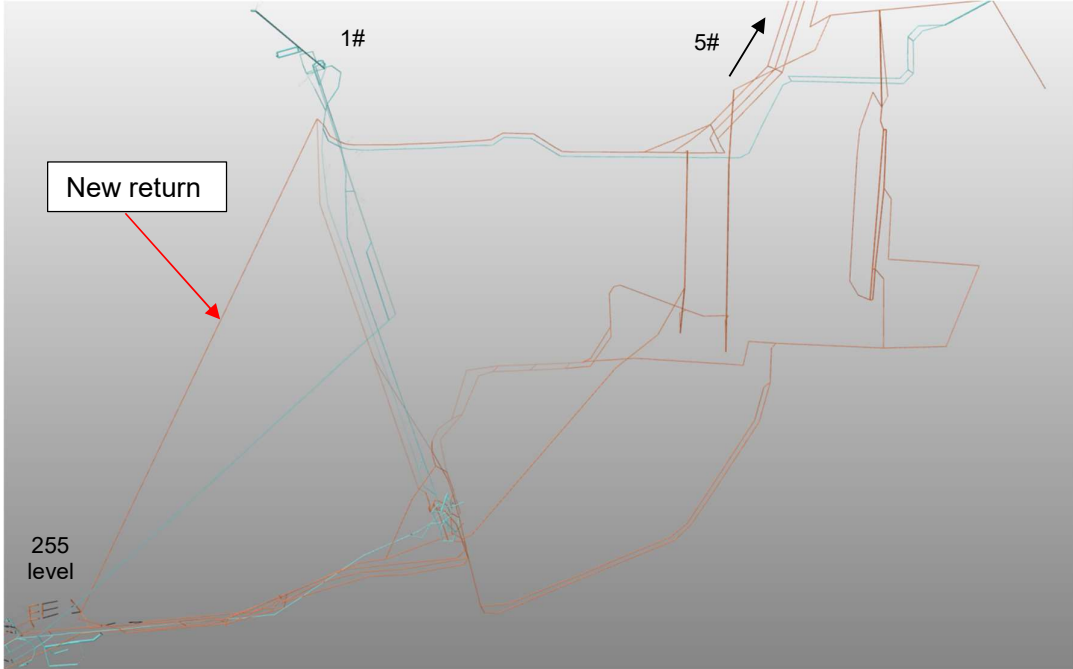
A₁

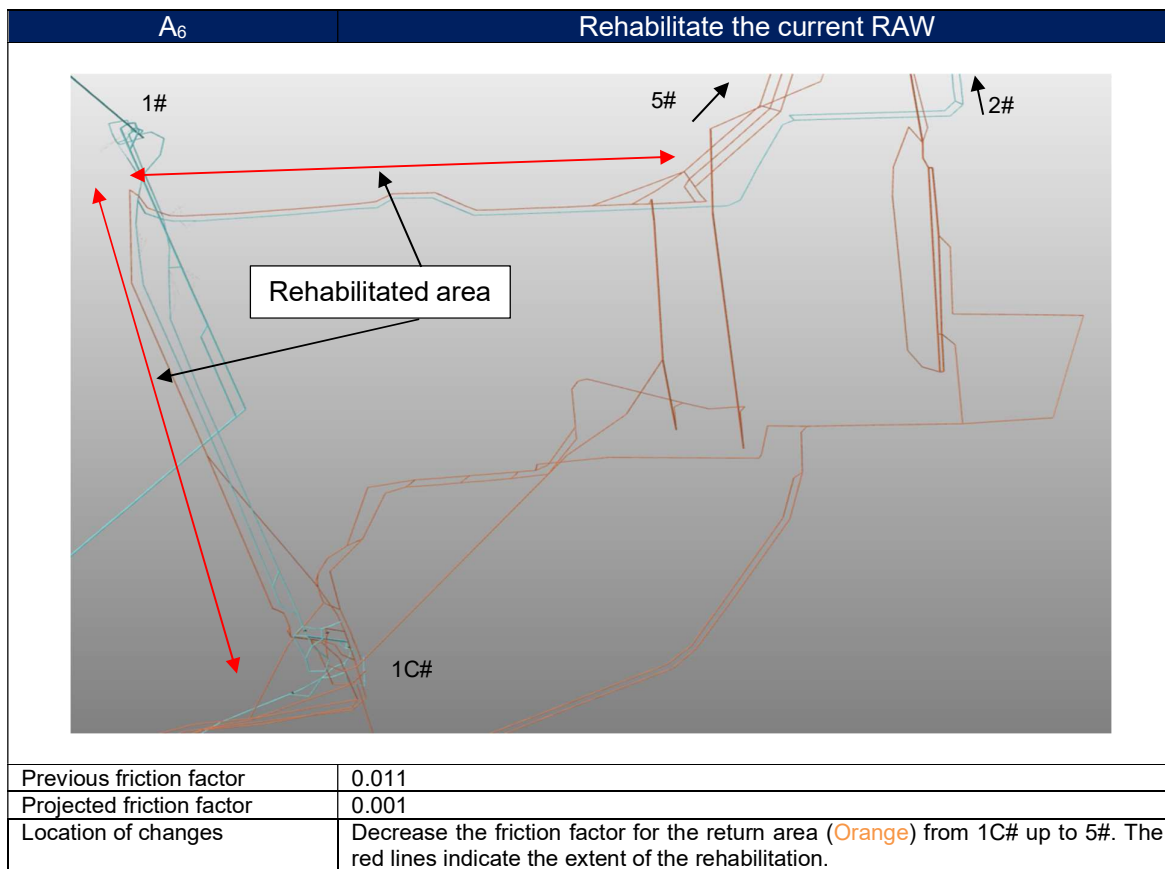
Additional /new shaft

The diagram illustrates a 3D model of a mine's underground ventilation network. A central 'Mining block' is shown with a complex arrangement of tunnels and shafts. Five specific shafts are labeled: 1#, 2#, 5#, and two others indicated by a box labeled 'New shafts' with arrows pointing to blue and red lines. The shafts are represented by orange and blue lines, showing their vertical and horizontal connections within the mine's structure.

Shaft diameter (m)	4.5 (circular)	
Friction factor (N ² /m ⁴) [24]	0.012 (Upcast)	0.11 (Downcast)
Fan size (MW)	2	
Development meters (m)	2426 (Upcast)	2270 (Downcast)
Link description	Upcast – Connected to the West return system of the mine Downcast – Connected at 291 level (Lowest part of the mine)	

A ₂ Cross-over	
	
Development meters (m)	231
Haulage size (m)	3 x 3
Nr. of doors added (Location)	2 (52 level at 1# and 2# side to access area – red block in the figure)
Nr. of doors removed (Location)	1 (52 level at 1C sub-shaft)
Nr. of walls build (Location)	5 (Two at 1# side and three walls at 1C# to close the old intake)
A ₃ Condenser pond 5	
	
Heat exchange capacity (kW)	3 950
Nr. of spray ponds	3
Fan size (kW)	500
Fan capacity (kg/s)	69.4
Nr. of walls build (Location)	4 (In the 270 RAW connected to the condenser chamber)

A ₄	Additional fans in RAW
	
Nr. of fans installed	2
Fan location	Fan 1 – West RAW, Fan 2 – East RAW
Fan size (kW)	500
Fan capacity (kg/s)	Fan 1 – 160, Fan 2 – 153
Nr. of fans removed	17 (Six fans on 273, Three fans on 280, Two fans each on 291, 289, 287, 284)
A ₅	New RAW to 1#
	
Development meters (m)	2 300
Haulage size (m)	3 x 3
Description	Return haulage starts at the back of the condenser ponds up to 1# on 52 level where it returns into the RAW going to 5#.



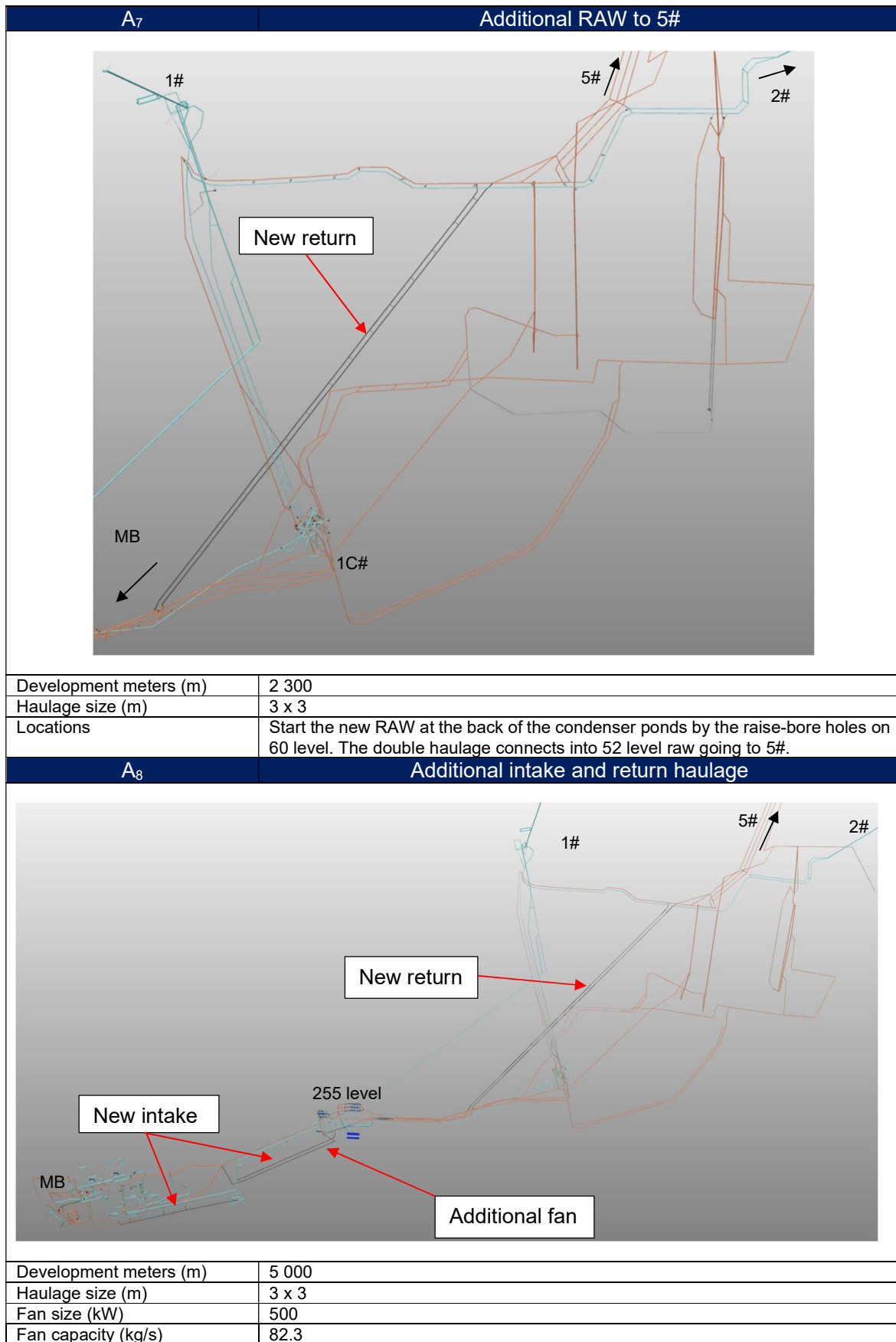
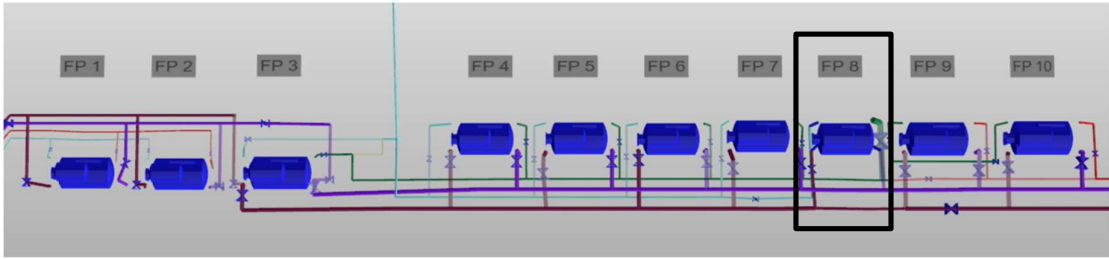
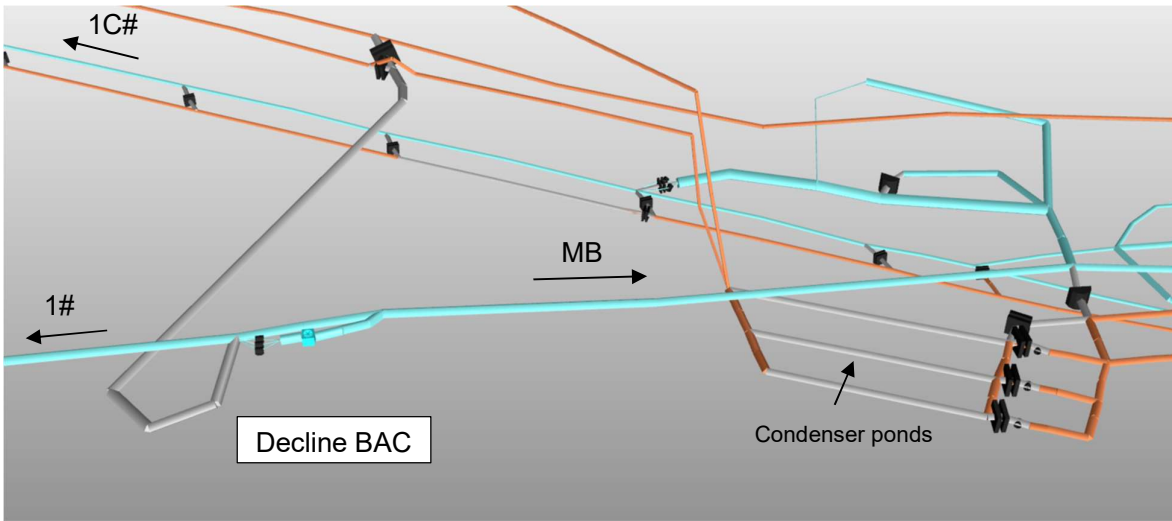
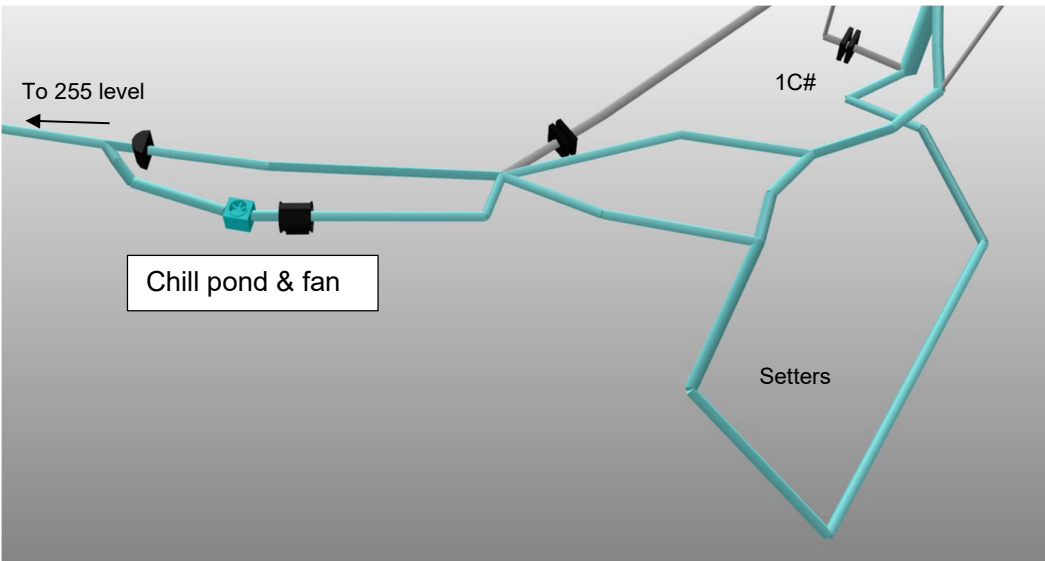
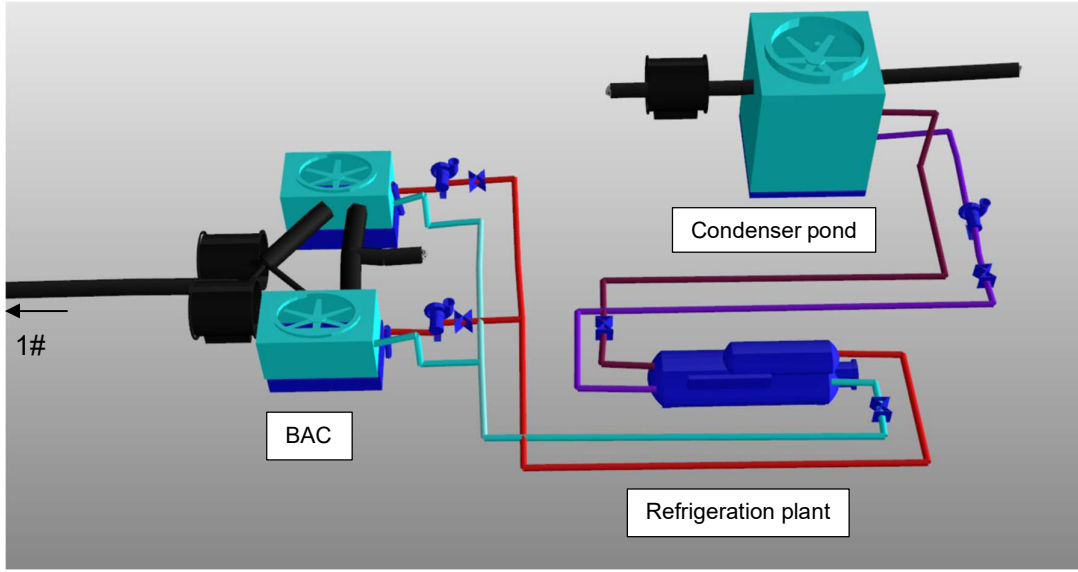
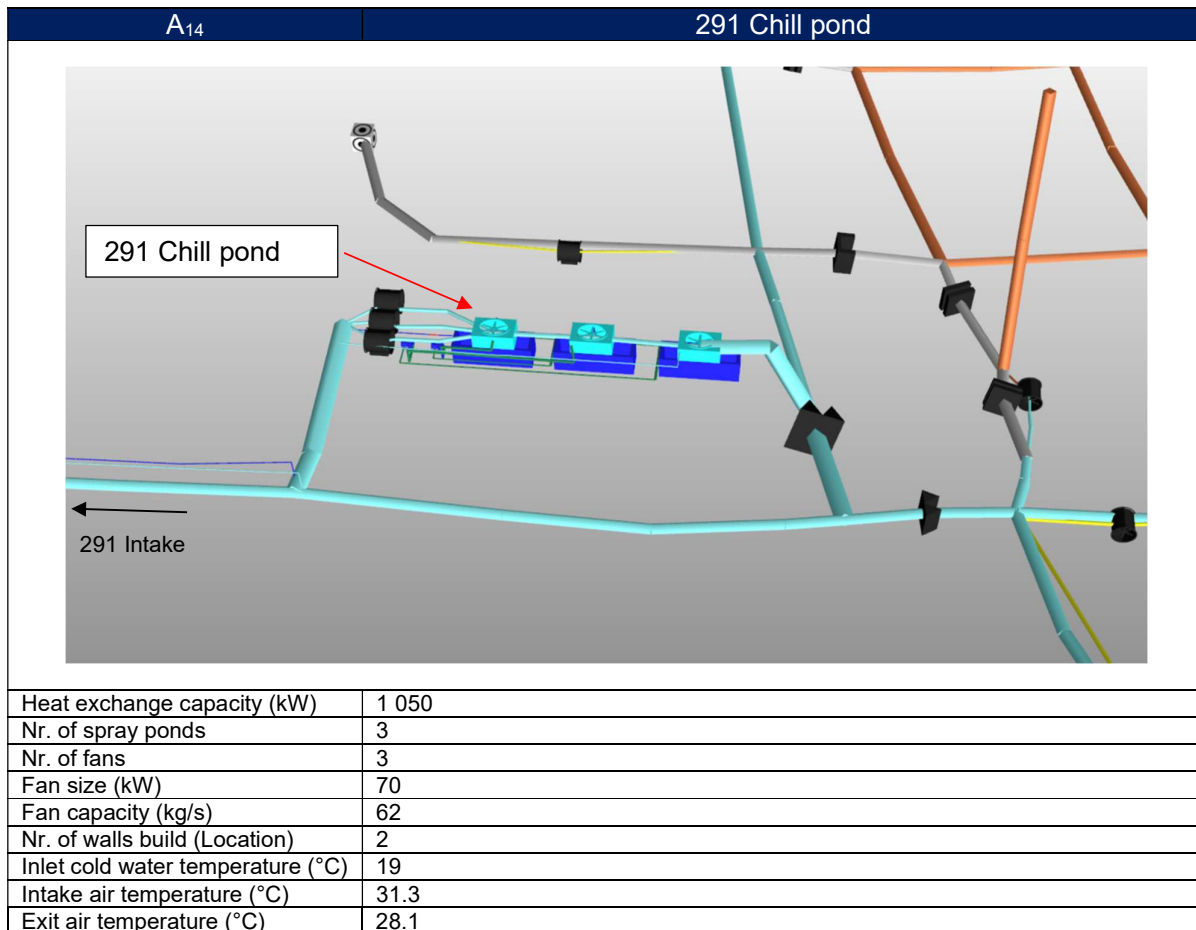


Table D-2: Changes to the baseline simulation model per project - Cooling

A ₉ Underground refrigeration	
	
Additional refrigeration plant	FP8 (HM20)
Additional cooling (kW)	15 065
Cold water temperature (°C)	8.9
Configuration	Added to the CC2 Lag machines
A ₁₀ Intake air BAC (Decline)	
	
Airflow (kg/s)	133.3
Cooling (kW)	5 700
Intake air temperature (°C)	28.4
Exit air temperature (°C)	16.8
Location	In the main intake airway before 255 level. The bulk of the air will be called before arriving to the BAC

A ₁₁ Intake air BAC (1C sub-shaft)	
	
Goal (°C)	11.5
Airflow (kg/s)	46
Cooling (kW)	2 300
Location	Located on the 64 level at 1C# to 255 level
A ₁₂ Surface refrigeration	
	
Goal (°C)	6
Airflow (kg/s)	200
Cooling (kW)	8 000
Location	Refrigeration plant and system on the surface that ties into the 1# downcast.
A ₁₃ Electric vehicles	
Current Diesel fleet heat load (kW)	14 990 (Utilised equipment heat load 6745 kW)
Battery electric fleet heat load (kW)	3 910 (Utilised equipment heat load 1760 kW)
Changes made	Changed the heat value of the AirTunnel in PTB, a kW/m value based on the diesel machinery fleet. The diesel fleets' heat load must be multiplied by 0.26 to represent the battery electric fleet.



Detailed air cooling power values

The air cooling power values for each level of the proposed projects are shown in Table D-3, Table D-4 and Table D-5.

Table D-3: Change in ACP for a level of the different projects (A₁-A₅)

Symbol	A ₀	A ₁	A ₂	A ₃	A ₄	A ₅
Level	Baseline	Additional /new shaft	Cross-over	Condenser 5	Additional fans in the RAW	New straight RAW to 1#
ΔACP	0	311.2	18.1	205.7	480.8	66.3
MB inlet total	2342.6	2653.8	2360.7	2548.2	2823.3	2408.8
272	514.9	605.1	512.7	579.5	456.9	545.1
273	271.3	438.0	267.4	403.4	577.2	327.3
280	370.7	411.4	374.5	340.5	472.3	364.0
284	373.3	209.6	381.1	381.0	408.6	355.5
287	274.0	323.0	278.9	272.6	361.3	268.7
289	250.1	324.8	253.0	267.6	229.8	261.2
291	288.4	341.9	293.1	303.6	317.2	287.1

Table D-4: Change in ACP for a level of the different projects (A₆-A₉)

Symbol	A ₀	A ₆	A ₇	A ₈	A ₉
Level	Baseline	Rehabilitate the current RAW	Additional RAW to 5#	Additional intake and return haulage	Underground refrigeration
ΔACP	0	44.2	102.5	22.4	397.9
MB inlet total	2342.6	2386.7	2445.1	2364.9	2740.4
272	514.9	528.8	559.0	593.5	633.7
273	271.3	282.6	325.5	393.0	346.1
280	370.7	373.5	369.2	311.4	496.3
284	373.3	378.5	364.3	310.2	156.6
287	274.0	279.1	272.3	255.1	402.6
289	250.1	252.3	262.6	238.0	356.8
291	288.4	292.0	292.2	263.8	348.4

Table D-5: Change in ACP for a level of the different projects (A₁₀-A₁₃)

Symbol	A ₀	A ₁₀	A ₁₁	A ₁₂	A ₁₃	A ₁₄
Level	Baseline	Intake air BAC (Decline)	Intake air BAC (1C sub-#)	Surface ref.	Electric vehicles	291 Chill pond
ΔACP	0	703.7	32.6	770.2	61.7	194.4
MB inlet total	2342.6	3046.2	2375.1	3112.7	2404.3	2537.0
272	514.9	653.3	558.8	669.8	533.0	443.4
273	271.3	323.2	296.9	350.9	281.4	285.0
280	370.7	445.0	394.3	459.9	373.6	761.1
284	373.3	534.9	231.1	520.7	372.6	390.7
287	274.0	383.0	329.5	383.1	273.2	361.5
289	250.1	316.0	279.1	328.4	261.6	452.8
291	288.4	390.7	285.4	399.9	309.1	127.2

APPENDIX E: DETAILED COST ANALYSIS

The cost analysis entails that some costs will be the same for each project, such as the cost per development meter. Table E-1 is the constant development cost used during the cost analysis.

Table E-1: Constant development cost used during cost analysis⁴

Description	Cost (R/m)
Development meters (traditional 3x3)	95 539
Development meters (trackless 4x4)	142 955

Table E-2 will show the cost analysis for each project based on quotes.

Table E-2: Cost analysis - detail

A ₁	Additional /new shaft	
Capex (Quote)	Charges	Cost (R)
	Fix charge	6 022 000
	Time-related	235 755 000
	Raise boring	111 221 000
	Directional drilling	19 195 000
	Two extraction fans	2 000 000
	Total	374 193 000
A ₂	Cross-over	
Capex (Quote)	Charges	Cost (R)
	Development meters (231m, 3x3)	22 069 000
	Total	22 069 000
A ₃	Condenser 5	
Capex (Quote)	Charges	Cost (R)
	Development (124m, 4x4)	17 726 000
	Auxiliaries	4 852 000
	Total	25 430 000
A ₄	Additional fans in the RAW	
Capex (Quote)	Charges	Cost (R)
	2 Fans	45 713 000
	Development (16m, 4x4)	2 287 000
	Total	48 000 000

⁴ Constant development cost received from mine's financial department

A ₅ New straight RAW to 1#		
Capex (Quote)	Charges	Cost (R)
	Development (2300m, 3x3)	219 739 000
	Total	219 739 000
A ₆ Rehabilitate the current RAW		
Capex (Quote)	Charges	Cost (R)
	Rehabilitate (1772m, 3x3)	21 174 000
	Total	21 174 000
A ₇ Additional RAW to 5#		
Capex (Quote)	Charges	Cost (R)
	Development (5000m, 3x3)	477 695 000
	Fan (500 kW)	17 143 000
	Total	494 838 000
A ₈ Additional intake and return haulage		
Capex (Quote)	Charges	Cost (R)
	Development (8373m, 3x3)	799 948 000
	Fan (500 kW)	17 143 000
	Total	817 091 000
A ₉ Underground refrigeration		
Capex (Quote)	Charges	Cost (R)
	HM20 plant	10 434 045
	Installation	4 953 000
	Moving cost	928 000
	Total	16 315 000
A ₁₀ Intake air BAC (Decline)		
Capex (Quote)	Charges	Cost (R)
	Development (10m, 4x4)	1 420 000
	Refrigeration machine package	12 777 000
	Mechanical	9 174 000
	Water pipe/installation	928 000
	Structural and mechanical installation	2 666 000
	Electrical	10 275 000
	Control and instrumentation	2 650 000
	Engineering & project management	4 500 000
	Total	44 390 000
A ₁₁ Intake air BAC (1C sub-shaft)		
Capex (Quote)	Charges	Cost (R)
	Development (10m, 4x4)	1 420 000
	KTI UG 500kW	30 000 000
	Structural and mechanical installation	1 258 000
	Mechanical	5 904 000
	Total	38 582 000

A ₁₂	Surface refrigeration			
Capex (Quote)	Charges			Cost (R)
	Civil works			2 773 000
	Structural steelwork			862 000
	Refrigeration machine package			12 777 000
	Mechanical package			9 174 000
	Water piping/ insulation			928 000
	Structural and mechanical installation			2 666 000
	Electrical			10 275 000
	Control and instrumentation			2 650 000
	Engineering and project management			4 500 000
	Total			46 605 000
A ₁₃	Electric vehicle			
Capex (Quote)	Charges	Difference in cost to diesel machinery	Quantity	Cost (R)
	Sandvik 514	1 400 000	5	7 000 000
	Atlas Copco ST	6 000 000	1	6 000 000
	Torrow 1400	6 000 000	1	6 000 000
	Trucks	4 000 000	10	40 000 000
	4.0l 4x4 bakkies	1 600 000	15	24 000 000
	3.0l 4x4 bakkies	1 600 000	10	16 000 000
	Total			99 000 000
The mine is supposed to buy new diesel mechanised machinery, and planned capital is already available. The change from diesel machinery to battery-electric vehicles will need additional capital because the electric vehicles' are more costly. This project will entail only the capital cost required to enable the changeover to battery-electric vehicles.				
A ₁₄	291 Chill pond			
Capex (Quote)	Charges			Cost (R)
	Development (108 m, 4x4)			15 489 000
	Civil, mechanical, and equipment			2 500 000
	Total			17 989 000

APPENDIX F: PROJECT POWER USAGE

The power usage of each project is calculated by an internal calculation tool within the PTB simulation software. The project's annual power is in Table F-1.

Table F-1: Project power usage.

Symbol	Project	Annual power usage (GW)	Difference in power usage
A ₀	Baseline	116.63	-
A ₁	Additional/new shaft	129.89	13.266
A ₂	Cross-over	116.23	-0.401
A ₃	Condenser 5	124.58	7.953
A ₄	Additional fans in the RAW	120.06	3.430
A ₅	New straight RAW	115.92	-0.706
A ₆	Rehabilitate the current RAW	116.01	-0.614
A ₇	Additional RAW	117.74	1.116
A ₈	Additional intake and return haulage	119.42	2.797
A ₉	Underground refrigeration	135.60	18.970
A ₁₀	Intake air BAC (Decline)	138.09	21.465
A ₁₁	Intake air BAC (1C sub-shaft)	137.30	20.668
A ₁₂	Surface refrigeration	135.15	18.527
A ₁₃	Electric vehicle	116.83	0.203
A ₁₄	291 Chill pond	118.35	1.726

APPENDIX G: PUBLISHED ARTICLE

The article titled "*Prioritisation of environmental projects in deep-level mine ventilation systems*" has been published in the journal of Mining, Metallurgy & Exploration. Figure G-1 is the confirmation that the article has been published online.

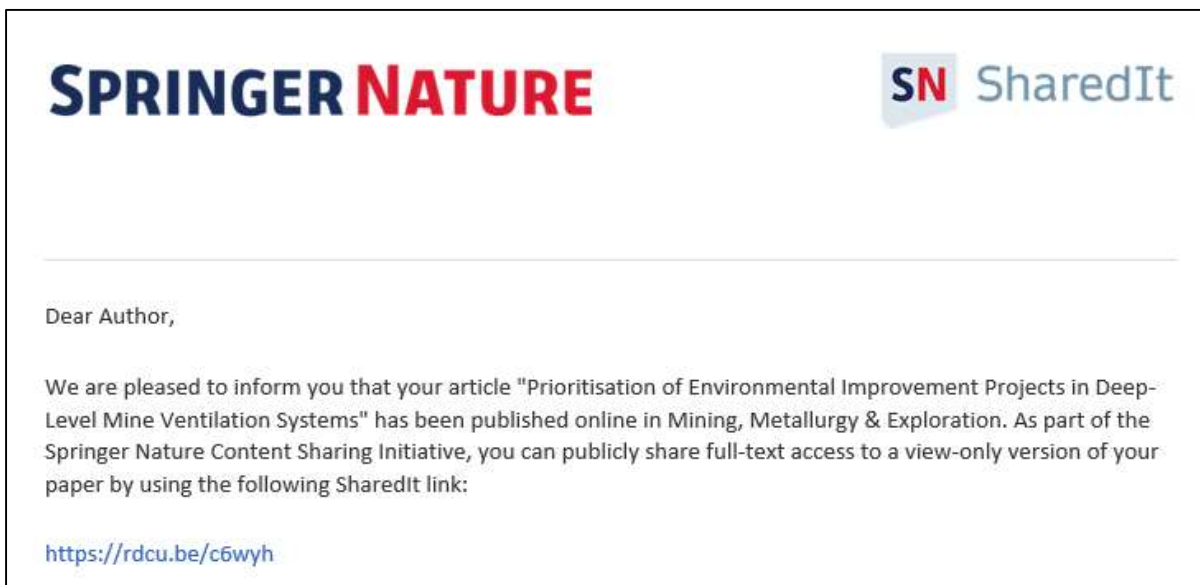


Figure G-1: Confirmation of the published article

Mining, Metallurgy & Exploration
<https://doi.org/10.1007/s42461-023-00738-w>



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

J. Swanepoel¹ · J. C. Vosloo¹ · J. H. van Laar¹  · W. A. Pelser²

Received: 5 October 2022 / Accepted: 1 February 2023
© The Author(s) 2023

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

✉ J. Swanepoel
jswanepoel@nms2.com

¹ Center for Research and Continued Engineering Development (CRCED) Pretoria, North-West University, Pretoria, South Africa

² Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa

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 countless 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 no.
	A	B	C	
Acuña, Baiden, Gruting, Jacobs			x	[6], [44]–[46]
Ali, Amorcho, Asr, Javanshirgivi	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, Musingswini, Owusu-Mensah, Özfrat, 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

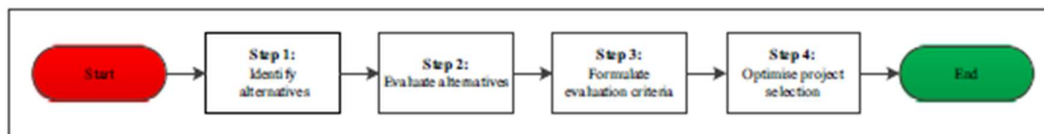


Fig. 1 New prioritising method for environmental improvement projects

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 $\pm 30\%$ [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

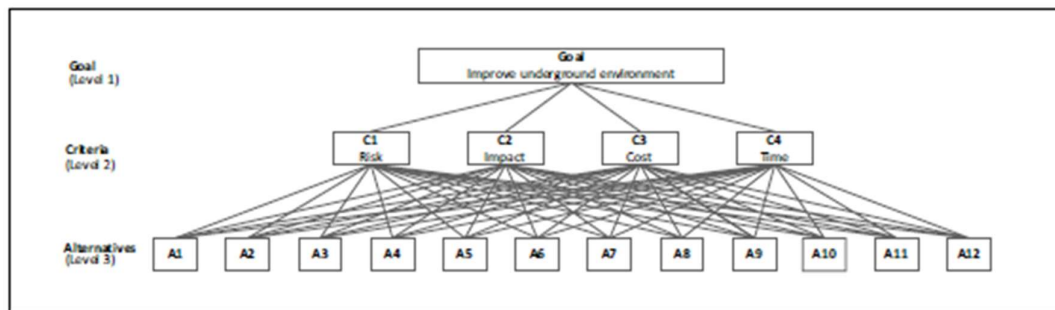


Fig. 2 Schematic framework of the AHP method

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].

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

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).

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

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.

$$[CV] = [A] \cdot [W] \quad (3)$$

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

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

where,

λ_i eigenvalue
 cv_i consistency element

The highest eigenvalue is calculated using Eq. 5.

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

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

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

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

$$CR = \frac{CI}{RI} \quad (7)$$

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.

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

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.

$$V_{ij} = W_i \times \bar{R}_{ij} \quad (9)$$

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].

$$V^+ = \{v^+_1, v^+_2, \dots, v^+_n\} = \{(\max_j v_{ij} | icl^+), (\min_j v_{ij} | icl^-)\} \quad (10)$$

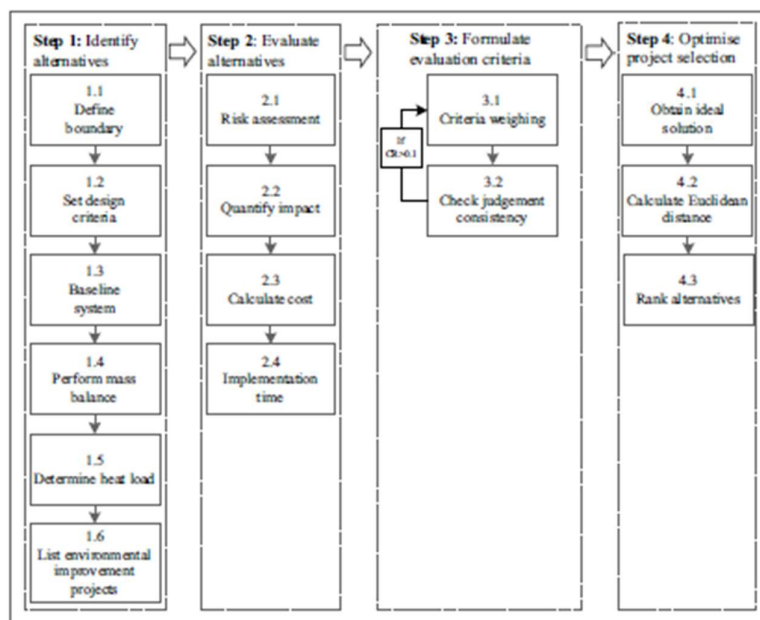
$$V^- = \{v^-_1, v^-_2, \dots, v^-_n\} = \{(\min_j v_{ij} | icl^+), (\max_j v_{ij} | icl^-)\} \quad (11)$$

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].

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

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

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 particulate 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.

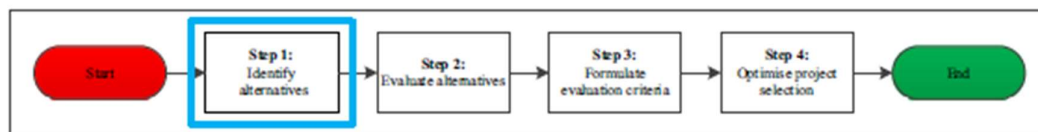
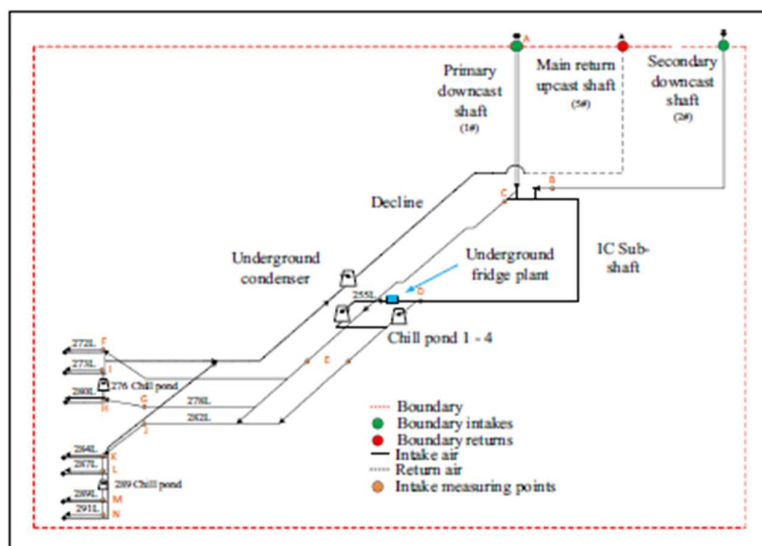


Table 8 Mine design criteria

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

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

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

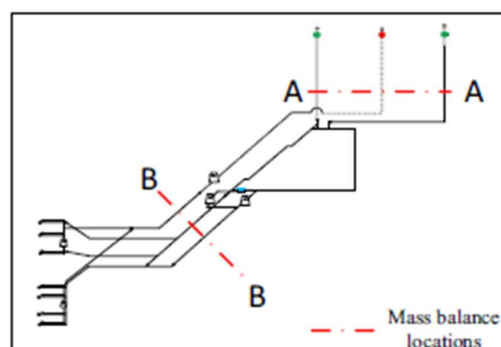


Fig. 6 Locations of the mass balance for the mine

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

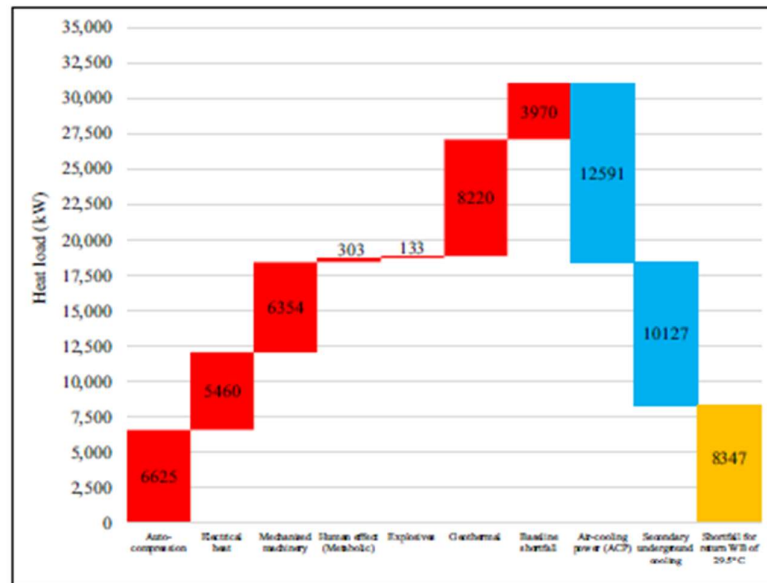


Table 12 Proposed alternatives to rectify the airflow quantity

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

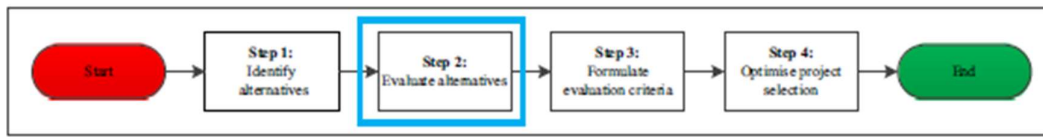


Fig. 8 Step 2 of the method - evaluate alternatives

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 (IC 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).

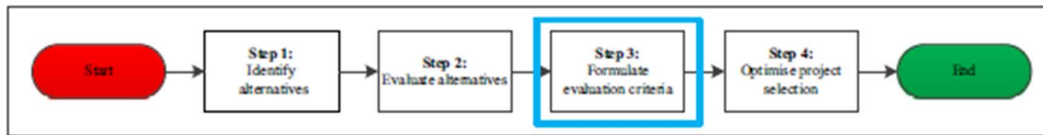


Fig. 9 Step 3 of the method - formulate evaluation criteria

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.

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

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.

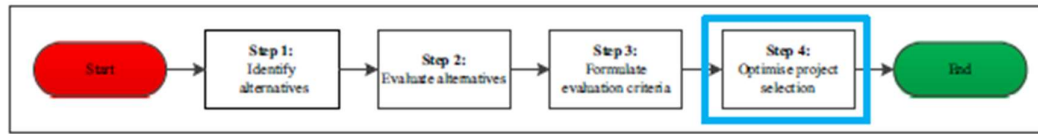


Fig. 10 Step 4 of the method - optimise project selection

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 IC 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

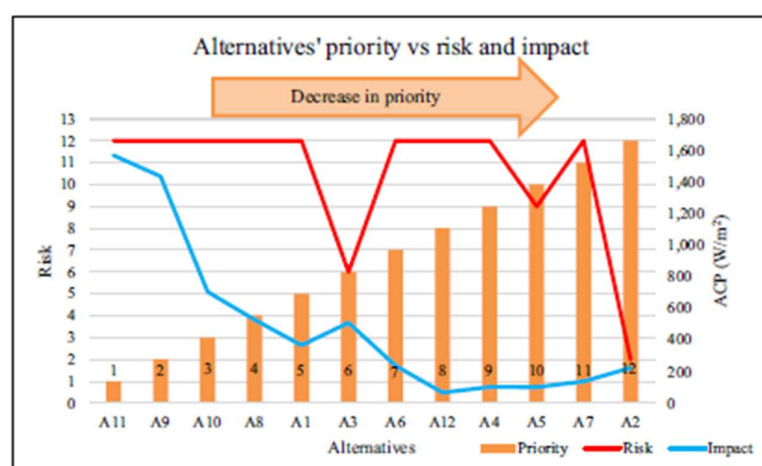
Table 18 Euclidean distance to the NIS and PIS

	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 (A_1) and six (A_3), as well as priority 10 (A_5) and 11 (A_7).

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 A_2 , the condenser pond 5. The projects were financially motivated, as indicated in Fig. 11 that shows A_2 is prioritised last, based on the criteria used in this method. Although alternative A_2 is the cheapest option, the risk rating and impact of the alternative on the underground environment are low. Currently, A_2 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 (A_{11}) 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/m^2 . 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.

Funding Open access funding provided by North-West University. This work was sponsored by ETA Operations (Pty) Ltd, South Africa.

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

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Hartnady CJH (2009) South Africa's gold production and reserves. *S Afr J Sci* 105:9–10
- Watney D (2019) "Gold Cost Curves | Minxcon Group." *Minxcon Group*, Dec. 09, 2019. <https://www.minxcon.co.za/december-2019-gold-cost-curves/> (accessed Aug. 21, 2022)
- du Plessis J (2014) Ventilation and occupational environment engineering in mines, 3rd edn. Mine Ventilation Society of South Africa, Johannesburg
- "Gold Focus 2020," London, 2020. [Online]. Available: www.metalsfocus.com
- Acuña EI, Lowndes IS (2014) A review of primary mine ventilation system optimization. *Interfaces (Providence)* 44(2):163–175. <https://doi.org/10.1287/INTE.2014.0736>
- Baiden G, Bissiri Y, Hardcastle S and Kocsis V (2005) "Justification of 'on-demand' ventilation systems by means of simulation techniques," in *Application of Computers and Operations Research in the Mineral Industry - Proc. of the 32nd Int. Symposium on the Application of Computers and Operations Research in the Mineral Industry, APCOM 2005*, A.A. Balkema Publishers 457–462.
- Bascompta MM, Castañón AM, Sanmiquel L, Oliva J (2016) "Heat flow assessment in an underground mine an approach to improve the environmental conditions. *DYNA* 83(197):174. <https://doi.org/10.15446/DYNA.V83N197.52182>
- Cheng J et al (2014) Comprehensive and integrated mine ventilation consultation model - CIMVCM. *Tunn Undergr Sp Technol* 45:166–180. <https://doi.org/10.1016/j.trust.2014.09.004>
- du Plessis J, Hoffmon D, Marx V, van der Westhuizen R (2013) "Optimising ventilation and cooling system for a operational mine using network simulation models."
- Krog R, Grau R, Mucho T and Robertson S (2004) "Ventilation planning layouts for large opening mines," in *Proceedings of the society for mining, metallurgy, and exploration annual meeting*, 1–9
- Mackay L, Bluhm S, van Rensburg J (2010) "Refrigeration and cooling concepts for ultra deep platinum mining", in *The 4th International Platinum Conference, Platinum in transition 'Boom or Bust' Conference Proceedings*. Sun City, South Africa 2010:285–292
- Mare P (2015) Improved implementation strategies to sustain energy saving measures on mine cooling system. University of North West, Potchefstroom, South Africa
- Nel AJH, Vosloo JC, Mathews MJ (2018) Evaluating complex mine ventilation operational changes through simulations. *J Energy South Africa* 29(3):22–32. <https://doi.org/10.17159/2413-3051/2018/V29I3A4445>
- Sasmito AP, Birgersson E, Ly HC, Mujumdar AS (2013) Some approaches to improve ventilation system in underground coal mines environment – a computational fluid dynamic study. *Tunn Undergr Sp Technol* 34:82–95. <https://doi.org/10.1016/j.trust.2012.09.006>
- Mathews I, van Laar JH, Arndt D, Vosloo JC and Seetal G (2021) "Integrated dynamic simulation method for deep-level mine cooling system planning," in *SAIIE 32*, 669–686
- Danko G, Bahrami D, Stewart C (2020) Applications and verification of a computational energy dynamics model for mine climate simulations. *Int J Min Sci Technol* 30(4):483–493. <https://doi.org/10.1016/j.ijmst.2020.03.019>
- Wallace K, Prosser B, Stinnette JD (2015) The practice of mine ventilation engineering. *Int J Min Sci Technol* 25(2):165–169. <https://doi.org/10.1016/j.ijmst.2015.02.001>
- Bluhm S, Moreby R, von Glehn F, Pascoe C (2014) "Life-of-mine ventilation and refrigeration planning for Resolution

- Copper Mine." *J South African Inst Min Metall* 114(6):497–503 Accessed: Aug. 20, 2022. [Online]. Available: http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S2225-62532014000600016.
19. De Souza E (2007) Optimization of complex mine ventilation systems with computer network modelling. *IFAC Proc* 40(11):323–329. <https://doi.org/10.3182/20070821-3-CA-2919.00049>
 20. du Plessis J, Marx WM, Nell C (2014) "Efficient use of energy in the ventilation and cooling of mines," in A Southern African silver anniversary meeting, 114(12)
 21. Schluse M, Atorf L, Rossmann J (2017) "Experimentable digital twins for model-based systems engineering and simulation-based development." <https://doi.org/10.1109/SYSCON.2017.7934796>
 22. Gupta S, Kumar U (2012) "An analytical hierarchy process (AHP)-guided decision model for underground mining method selection." 26(4):324–336 <https://doi.org/10.1080/17480930.2011.622480>
 23. Peskens TW, Buxton MW, Rinne M, Vervoort IA (2013) Underground mining method selection and preliminary techno-economic mine design for the Wombat orebody. Delft University of Technology
 24. Pinzon Amorcho JA, Hartmann T (2022) A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods. *J Build Eng* 53:104596. <https://doi.org/10.1016/j.jobe.2022.104596>
 25. Gulum P, Ayyildiz E, TaskinGumus A (2021) A two level interval valued neutrosophic AHP integrated TOPSIS methodology for post-earthquake fire risk assessment: an application for Istanbul. *Int J Disaster Risk Reduct* 61:102330. <https://doi.org/10.1016/j.jidrr.2021.102330>
 26. Lin R, Lu S, Yang A, Shen W, Ren J (2021) Multi-criteria sustainability assessment and decision-making framework for hydrogen pathways prioritization: an extended ELECTRE method under hybrid information. *Int J Hydrogen Energy* 46(24):13430–13445. <https://doi.org/10.1016/j.ijhydene.2021.01.018>
 27. Nhung LTH, Phung TT, Nguyen HMY, Le TN, Nguyen TA, Vo TD (2022) Load shedding in microgrids with dual neural networks and AHP algorithm. *Eng Technol Appl Sci Res* 12(1):8090–8095. <https://doi.org/10.48084/ESTASR.4652>
 28. Jorissen P, Moons K, Pintelon L, De Ridder D, Everaerts W (2019) Identification of multi-stakeholder value in prostate cancer treatment by application of Multi-Criteria Decision Making (MCDM). *Eur Urol Suppl* 18(1):e2184–e2185. [https://doi.org/10.1016/S1569-9056\(19\)31578-7](https://doi.org/10.1016/S1569-9056(19)31578-7)
 29. Yasmin M, Tatoglu E, Kilic HS, Zaim S, Delen D (2020) Big data analytics capabilities and firm performance: an integrated MCDM approach. *J Bus Res* 114:1–15. <https://doi.org/10.1016/j.jbusres.2020.03.028>
 30. Dayo-Olupona O, Genc B, Onifade M (2020) Technology adoption in mining: a multi-criteria method to select emerging technology in surface mines. *Resour Policy* 69:101879. <https://doi.org/10.1016/j.resourpol.2020.101879>
 31. Yavuz M (2015) Equipment selection based on the AHP and Yager's method. *J South African Inst Min Metall* 115(5):425–433. <https://doi.org/10.17159/2411-9717/2015/V115N5A10>
 32. Javanshirgivi M, Safari M (2017) The selection of an underground mining method using the fuzzy topsis method: a case study in the Kamar Mahdi II fluorine mine. *Min Sci* 24:161–181. <https://doi.org/10.5277/MS20172410>
 33. Kluge P, Malan DF (2011) The application of the analytical hierarchical process in complex mining engineering design problems. *J South African Inst Min Metall* 111:847–855
 34. Nourali H, Nourali S, Ataei M, Imanipour N (2012) A hierarchical preference voting system for mining method selection problem. *Arch Min Sci* 57(4):1057–1070. <https://doi.org/10.2478/V10267-012-0070-X>
 35. Kursunoglu N, Onder M (2015) Selection of an appropriate fan for an underground coal mine using the Analytic Hierarchy Process. *Tunn Undergr Sp Technol* 48:101–109. <https://doi.org/10.1016/j.tust.2015.02.005>
 36. Alpaz S, Yavuz M (2009) Underground mining method selection by decision making tools. *Tunn Undergr Sp Technol* 24(2):173–184. <https://doi.org/10.1016/j.tust.2008.07.003>
 37. Afrapoli AM (2018) A hybrid simulation and optimization approach towards truck dispatching problem in surface Mines. University of Alberta, Alberta
 38. Alpaz S, Yavuz M (2007) "A decision support system for underground mining method selection", in *New Trends in Applied Artificial Intelligence*. LNAI 4570:334–343
 39. Bogdanovic D, Nikolic D, Ilic I (2012) Mining method selection by integrated AHP and PROMETHEE method. *An Acad Bras Cienc* 84(1):219–233. <https://doi.org/10.1590/S0001-37652012000100023>
 40. Balusa BC, Gorai AK (2019) Sensitivity analysis of fuzzy-analytic hierarchical process (FAHP) decision-making model in selection of underground metal mining method. *J Sustain Min* 18(1):8–17. <https://doi.org/10.1016/j.jsm.2018.10.003>
 41. Hayati M, Hayati M, Rajabzadeh R, Darabi M (2015) Determination of optimal block size in angouran mine using VIKOR method. *J Mater Environ Sci* 6(11):3236–3244. [10.1.1.703.9386](https://doi.org/10.1.1.703.9386)
 42. Hudej M, Vujic S, Radosavlevic M, Ilic S (2013) Multi-variable selection of the main mine shaft location. *J Min Sci* 49(6):950–954. <https://doi.org/10.1134/S1062739149060154>
 43. Iphar M, Alpaz S (2018) A mobile application based on multi-criteria decision-making methods for underground mining method selection. *Int J Mining Reclam Environ* 33(7):480–504. <https://doi.org/10.1080/17480930.2018.1467655>
 44. Acuna E, Alvarez R, Hardcastle SG (2014) "A theoretical comparison of ventilation on demand strategies for auxiliary mine ventilation systems"
 45. Gruting U, Schutte CSL, Pelser WA, Laar JH (2022) Investigating the link between compressed air wastage and ventilation shortfalls in deep-level mines. *South African J Ind Eng* 33(3):109–123. <https://doi.org/10.1166/33-3-2786>
 46. Jacobs DR, Laar JH, Schutte CSL (2022) Strategy to identify and mitigate hazards in deep-level mine ventilation systems using a calibrated digital twin. *South African J Ind Eng* 33(3):204–217. <https://doi.org/10.1166/33-3-2795>
 47. Ali MAM, Kim JG (2021) Selection mining methods via multiple criteria decision analysis using TOPSIS and modification of the UBC method. *J Sustain Min* 20(2):49–55. <https://doi.org/10.46873/2300-3960.1054>
 48. Asr ET, Hayati M, Rafiee R, Ataie M, Jalali SE (2015) Selection of optimum tunnel support system using aggregated ranking of SAW, TOPSIS and LA methods. *Int J Appl Oper Res* 5(4):49–63
 49. du Plessis JJ, Hoffman D, Marx WM van der Westhuizen R (2013) "Optimising ventilation and cooling systems for an operating mine using network simulation models,"
 50. Kabwe E (2017) Optimal mining method selection for Nchanga's Upper Orebody using analytic hierarchy process and Yager's method. *Min Technol* 126(3):151–162. <https://doi.org/10.1080/14749009.2016.1274840>
 51. Yavuz M (2014) The application of the analytic hierarchy process (AHP) and Yager's method in underground mining method selection problem. *Int J Mining Reclam Environ* 29(6):453–475. <https://doi.org/10.1080/17480930.2014.895218>
 52. Balusa BC, Singam J (2018) Underground mining method selection using WPM and PROMETHEE. *J Inst Eng Ser D* 99(1):165–171. <https://doi.org/10.1007/S40033-017-0137-0/TABLES/12>

53. Wang C, Tu S (2015) "Selection of an appropriate mechanized mining technical process for thin coal seam mining." *Math Probl Eng* 2015 <https://doi.org/10.1155/2015/893232>
54. Owusu-Mensah F, Musingwini C (2011) Evaluation of ore transport options from Kweisi Mensah Shaft to the mill at the Obuasi mine. *Int J Mining Reclam Environ* 25(2):109–125. <https://doi.org/10.1080/17480930.2010.538988>
55. Ebrahimabadi A (2014) A fuzzy AHP approach to select the proper roadheader in Tabas Coal Mine. Project of Iran. Islamic Azad University, Qaemshahr
56. Wang C, Yang S, Jiang C-J, Wu G-Y, Liu Q-Z (2019) Monte Carlo analytic hierarchy process for selection of the longwall mining method in thin coal seams. *J South African Inst Min Metall* 119:1005–1012. <https://doi.org/10.17159/2411-9717/173752020>
57. Ataei M, Jamshidi M, Sereshki F, Jalali SME (2008) Mining method selection by AHP approach. *J South African Inst Min Metall* 108(12):741–749
58. Kazakidis VN, Mayer Z, Scoble MJ (2013) "Decision making using the analytic hierarchy process in mining engineering." *Min Technol* 113(1) <https://doi.org/10.1179/037178404225004274>
59. Yavuz M, Alpay S (2008) Underground mining technique selection by multicriterion optimization methods. *J Min Sci* 44(4):391–401. <https://doi.org/10.1007/S10913-008-0043-9>
60. Yavuz M, Iphar M, Onoe G (2008) The optimum support design selection by using AHP method for the main haulage road in WLC Tuncbilek colliery. *Tunn Undergr Sp Technol* 23(2):111–119. <https://doi.org/10.1016/j.tust.2007.02.001>
61. Kizil MS, Abdalla S, Canbulat I (2014) Underground coal mine layout selection using analytical hierarchy process. *Min Technol* 123(1):20–29. <https://doi.org/10.1179/1743286313Y.0000000053>
62. Yetkin ME, Özfırat MK (2019) Selection of thick coal seam mining method using analytic hierarchy process. *J Eng Technol Ind Appl* 5(20):6–11. <https://doi.org/10.5935/2447-0228.20190071>
63. Musingwini C, Minnitt R (2008) "Ranking the efficiency of selected platinum mining methods using the analytic hierarchy process (AHP)." in *Third International Platinum Conference 'Platinum in Transformation'*, 319–326
64. Jamshidi J, Ataei M, Sereshki F, Seyed MEJ (2009) The application of AHP approach to selection of optimum underground mining method, case study: Jajarm Bauxite Mine (Iran). *J Arch Min Sci* 54:103–117
65. Özfırat MK (2012) A fuzzy method for selecting underground coal mining method considering mechanization criteria. *J Min Sci* 48(3):533–544. <https://doi.org/10.1134/S1062739148030173>
66. Ghazikalayeh AR, Ebrahimabadi AA, Alavi II (2014) Selecting proper mining method using fuzzy AHP approach (case study: Qaleh-Zari Copper Mine of Iran). *J Appl Sci Agric* 9(1):1–10
67. Ibishi G, Yavuz M, Genis M (2020) "Underground mining method assessment using decision-making techniques in a fuzzy environment: case study, Trepça mine, Kosovo." *Min Miner Depos* <https://doi.org/10.33271/MINING14.03.134>
68. Bitarafan M, Ataei M (2004) Mining method selection by multiple criteria decision making tools. *J South African Inst Min Metall* 109(9):493–498. https://doi.org/10.10520/AJA0038223X_2888
69. Karadogan A, Kahrman A, Ozer U (2008) Application of fuzzy set theory in the selection of underground mining method. *J South African Inst Min Metall* 108(2):73–79
70. Saaty TL (1980) *The Analytic Hierarchy Process*. McGraw-Hill, Pittsburgh
71. Baloyi VD, Meyer LD (2020) The development of a mining method selection model through a detailed assessment of multi-criteria decision methods. *Results Eng* 8:100172. <https://doi.org/10.1016/j.rineng.2020.100172>
72. Nell D (2019) Practical determination of heat loads for existing deep level gold mines. North-West University
73. Friedenstein BM, Cilliers C, van Rensburg J (2018) Simulating operational improvements on mine compressed air systems. *South African J Ind Eng* 29(3):69–81. <https://doi.org/10.7166/29-3-2049>
74. Nel AJH, Arndt DC, Vosloo JC, Mathews MJ (2019) Achieving energy efficiency with medium voltage variable speed drives for ventilation-on-demand in South African mines. *J Clean Prod* 232:379–390. <https://doi.org/10.1016/j.jclepro.2019.05.376>
75. Clarke RD, De Souza E (2018) Life-of-mine ventilation planning at Diavik. *CIM J* 9(3):121–126. <https://doi.org/10.15834/CIMJ.2018.12>
76. Stinnette JD, De Souza E, Buchan RM (2013) Establishing total airflow requirements for underground metal/non-metal mines for tier IV diesel equipment. Queen's University, Ontario
77. McPherson MJ (2015) *Subsurface Ventilation Engineering*, 2nd edn. Mine Ventilation Services, Nottingham
78. Webber RCW, Franz RM, Marx WM, Schutte PC (2003) A review of local and international heat stress indices, standards and limits with reference to ultra-deep mining. *J South African Inst Min Metall* 103(5):313–324
79. Nel AJH (2018) Mine ventilation characterisation through simulations. North-West University
80. Biffi M, Stanton DJ (2008) "Cooling power for a new age," in *Third International Platinum Conference 'Platinum in Transformation'* 239–247
81. Donoghue AM, Sinclair MJ, Bates GP (2000) Heat exhaustion in a deep underground metalliferous mine. *Occup Environ Med* 57:165–174. <https://doi.org/10.1136/OEM.57.3.165>
82. Bernard FC, Grobler LJ (2012) "Baseline service level adjustment methodologies for energy efficiency projects on compressed air systems in the mining industry," in *2012 Proceedings of the 9th Industrial and Commercial Use of Energy Conference* 1–8.
83. Belle B, Biffi M (2018) Cooling pathways for deep Australian longwall coal mines of the future. *Int J Min Sci Technol* 28(6):865–875. <https://doi.org/10.1016/j.ijmst.2018.02.001>
84. du Plessis J, van der Bank M (2015) "In-stope dust control at Beatrix Gold mine."
85. del Castillo D (2012) Minimising the electrical power usage of large refrigeration installations on South African mines. *J mine Vent Soc South Africa* 65(4):6–13
86. Kamyar A, Mostafa Aminossadati S, Leonardi C, Sasmito A (2016) "Current developments and challenges of underground mine ventilation and cooling methods," in *16th Coal Operators' Conference*, 10–12.
87. Dehghani H, Ataei-pour M (2012) Determination of the effect of operating cost uncertainty on mining project evaluation. *Resour Policy* 37(1):109–117. <https://doi.org/10.1016/j.resourpol.2011.11.001>
88. Duijm NJ (2015) Recommendations on the use and design of risk matrices. *Saf Sci* 76:21–31. <https://doi.org/10.1016/j.ssci.2015.02.014>
89. Dey PK (2010) Managing project risk using combined analytic hierarchy process and risk map. *Appl Soft Comput* 10(4):990–1000. <https://doi.org/10.1016/j.asoc.2010.03.010>
90. Fair R, van Laar JH, Nell K, Nell D, Mathews EH (2021) Simulating the sensitivity of underground ventilation networks to fluctuating ambient conditions. *South African J Ind Eng* 32(3):42–51. <https://doi.org/10.7166/32-3-2616>
91. Ibarra-Gutiérrez S, Bouchard J, Laflamme M, Fytas K (2021) Project economics of lithium mines in Quebec: a critical review. *Extr Ind Soc* 8(4):100984. <https://doi.org/10.1016/j.exis.2021.100984>

92. Bullock RL (2011) SME Mining Engineering Handbook, 3rd edn. Society for Mining, Metallurgy & Exploration, Littleton, CO
93. Kun M, Topaloglu S, Malli T, Kun M, Topaloglu S, Malli T (2013) Evaluation of wheel loaders in open pit marble quarrying by using the AHP and Topsis approaches. Arch Min Sci 58(1):255–267. <https://doi.org/10.2478/AMSC-2013-0018>
94. Saaty TL (2008) "Decision making with the analytic hierarchy process" Int J Serv Sci 1(1) <https://doi.org/10.1504/IJSSCI.2008.017590>
95. Olson DL (2004) Comparison of weights in TOPSIS models. Math Comput Model 40(7–8):721–727. <https://doi.org/10.1016/j.mcm.2004.10.003>
96. Namin FS, Shahriar K, Basoetin A, Ghodsypour SH (2009) Practical applications from decision-making techniques for selection of suitable mining method in Iran. Gospod Surowcami Miner Resour Manag 25(3):57–77
97. Issa U, Saeed F, Miky Y, Alqurashi M, Osman E (2022) Hybrid AHP-Fuzzy TOPSIS approach for selecting deep excavation support system. Buildings 12(3):295. <https://doi.org/10.3390/BUILDINGS12030295>
98. Gustafson A, Lipsett M, Schunnesson H, Galar D, Kumar U (2014) Development of a Markov model for production performance optimization. Application for semi-automatic and manual LHD machines in underground mines. Int J Mining Reclam Environ 28(5):342–355
99. Mathews I, Mathews EH, van Laar JH, Hamer W, Kleingeld M (2020) A simulation-based prediction model for coal-fired power plant condenser maintenance. Appl Therm Eng 174:1–10. [10.1016/j.applthermaleng.2020.115294](https://doi.org/10.1016/j.applthermaleng.2020.115294)
100. Mare P (2016) Novel simulations for energy management of mine cooling systems. North-West University

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.