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ADVANCES IN SOCIAL HUMANITIES RESEARCH

A Systematic Approach to Rehabilitation Decision-Making Under Uncertainty: Application of FAHP and Sensitivity Analysis in Underground Mining

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Abstract

This study examines leadership integrity as an ethical climate mechanism influencing Green Strategic Human Resource Management (GSHRM) and sustainability performance at a public higher education institution in a post-conflict developing country. Although research on leadership and green human resource management (HRM) has expanded, leadership integrity remains underexamined as a distinct antecedent of GSHRM, particularly in underrepresented contexts such as Timor-Leste. Drawing on ethical climate theory and transformational leadership theory, this study tests a model that positions leadership integrity as an antecedent, GSHRM as a mediating organizational mechanism, and sustainability performance as the institutional outcome. A sequential explanatory mixed-methods design was employed at Universidade Nacional Timor Lorosa'e (UNTL). Quantitative data collected from 150 faculty members and administrative staff across 10 faculties were analyzed using partial least squares structural equation modeling (PLS-SEM) with 5,000 bootstrap subsamples, supplemented by a thematic analysis of 41 open-ended responses. The results indicate that leadership integrity has a positive and statistically significant effect on GSHRM ($\beta = 0.372$, $p < 0.001$), while GSHRM has a positive and statistically significant effect on sustainability performance ($\beta = 0.317$, $p < 0.001$). GSHRM partially mediates the relationship between leadership integrity and sustainability performance ($\beta = 0.118$, $p < 0.001$), with the direct effect remaining statistically significant ($\beta = 0.176$, $p < 0.001$). The qualitative findings reveal a persistent gap between formal sustainability policies and their practical implementation, further supporting the ethical climate explanation. This study concludes that leadership integrity establishes a foundation of credibility, GSHRM serves as the organizational mechanism, and sustainability performance represents the institutional outcome. These findings underscore the importance of translating formal sustainability commitments into consistently implemented practices within resource-constrained higher education institutions.

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INTRODUCTION

The mining industry plays a pivotal role in global economic development by supplying raw materials such as copper, gold, and rare earth elements for infrastructure, technology, and energy production (Patil et al., 2023; Pouresmaieli et al., 2023; Wirth & Kaźmierczak, 2026). However, the industry operates in an environment characterized by volatility, uncertainty, complexity, and ambiguity (VUCA). Commodity prices fluctuate significantly due to market dynamics and geopolitical tensions; geotechnical conditions, regulatory changes, and evolving environmental,

social, and governance (ESG) requirements introduce unpredictability; underground mining methods, such as block caving, involve complex interdependencies among production sequencing, ground stability, logistics, and safety systems; and decision-makers face uncertain trade-offs among safety, productivity, and costs under conditions of incomplete or conflicting information. These challenges underscore the need for robust, structured decision-making frameworks that explicitly address trade-offs and enable decision-makers to justify their choices through transparent and systematic reasoning.

Mining operations exemplify VUCA conditions in a particularly challenging environment. Underground operations are highly interconnected systems in which localized disruptions can rapidly escalate into schedule delays, cost overruns, or increased risk exposure (Bustos et al., 2024; Pereira et al., 2023). Block caving is a large-scale underground mining method characterized by high productivity and relatively low operating costs per tonne. It relies on gravity-assisted ore extraction through the progressive fracturing and downward movement of the orebody following undercutting. Once caving is initiated, the rock mass continues to respond dynamically through stress redistribution, deformation, and fragmentation. Consequently, damage to an individual drawpoint, access drift, or production panel may affect adjacent areas because production depends on interconnected ore flows, equipment operations, ventilation systems, and production sequencing. In this study, rehabilitation refers to operational interventions aimed at restoring the safe and productive functionality of damaged, deteriorated, or underperforming production panels, including drawpoints, access drifts, ground support systems, and associated infrastructure. These interventions are time-sensitive because delays can reduce production rates and increase operational costs (Tasse et al., 2020). Furthermore, rehabilitation decisions involve multiple evaluation criteria and uncertain factors, including geotechnical conditions, equipment and labor availability, and cost implications (Hosseini et al., 2024; Potvin & Wesseloo, 2013; Todd, 2007).

The rehabilitation of production panels should therefore be regarded as a strategic decision-making process rather than merely a technical maintenance activity. When a high-capacity or high-grade production panel requires rehabilitation, temporarily closing the panel may improve risk management and long-term operational reliability but can also jeopardize short-term production targets, particularly when production forecasts fail to account for rehabilitation-related downtime or when rehabilitation resources are insufficient. Premature or excessive rehabilitation of otherwise productive areas may reduce operational performance, whereas postponing necessary rehabilitation may temporarily sustain production output but allow structural deterioration, access restrictions, and maintenance backlogs to accumulate. At the Alpha Block Cave (ABC) underground mine, rehabilitation planning and production panel closure decisions are frequently initiated only when deterioration becomes visibly apparent or when established risk thresholds necessitate immediate intervention. As presented in Table 1, actual production panel availability remained below the established target of 75% throughout the observed months, highlighting a persistent operational performance gap and the need for a more systematic rehabilitation decision-making framework to support management in achieving or exceeding the target.

Table 1. Panel Availability: Actual versus Target

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Expected
Actual (%)	65	66	70	67	70	66	74	71	69	69	70	67	75
Target (%)	75	75	75	75	75	75	75	75	75	75	75	75	–

Source: Internal data of the ABC mine, converted from the original line chart.

Currently, decisions regarding rehabilitation priorities and temporary production panel restrictions are not consistently supported by a transparent, standardized framework applicable across different panels and operating conditions. Consequently, these decisions may vary depending on the local operational context, available information, production pressures, and stakeholder judgments. This inconsistency creates uncertainty for engineers who must balance production output, resource availability, and geotechnical risks, particularly when affected panels contain high-grade ore or are strategically important for achieving short-term production targets. Rehabilitation decisions also require cross-functional coordination. Operations management and the strategic production planning team possess substantial decision-making authority and a high level of interest because these decisions directly affect production targets, panel availability, production sequencing, and resource allocation priorities. Geotechnical specialists exert significant technical influence because their assessments provide the foundation for evaluating ground stability and associated risks, while construction, development, and engineering teams are responsible for planning and executing rehabilitation activities. Delaying rehabilitation to maintain production may exacerbate ground deterioration and result in more severe operational disruptions. Conversely, excessively conservative panel closures without a systematic decision-making basis may lead to avoidable production capacity losses and inefficient allocation of rehabilitation resources.

Multi-criteria decision-making (MCDM) methods are particularly suitable for addressing such challenges, as they enable decision-makers to balance competing objectives while systematically incorporating subjective judgments rather than attempting to eliminate them. A comprehensive review of MCDM applications in mining and mineral processing identified the Analytic Hierarchy Process (AHP) as the most widely used technique for selection problems and highlighted the increasing adoption of hybrid decision-making approaches (Sitorus et al., 2019). Similarly, the mine planning literature documents a broad range of MCDM techniques, including AHP, outranking methods, ranking approaches, and fuzzy-based models, that accommodate uncertainty and linguistic judgments (Mahase et al., 2016). AHP structures complex decision problems into hierarchical levels and derives relative priorities through pairwise comparisons (Saaty, 1977). This method has been extensively applied to planning, resource allocation, and prioritization problems across various disciplines (Vaidya & Kumar, 2006). However, conventional AHP relies on precise numerical judgments, which may inadequately represent the ambiguity and uncertainty inherent in expert assessments. Fuzzy set theory (Zadeh, 1965) and Buckley's fuzzy hierarchical analysis approach (Buckley, 1985) address this limitation by enabling linguistic judgments to be represented using fuzzy numbers. In the mining sector, the Fuzzy Analytic Hierarchy Process (FAHP) has primarily been applied to underground mining method selection (Bajić et al., 2020; Balusa & Gorai, 2021), while sensitivity analysis has been employed

to assess the stability and robustness of FAHP-derived rankings under varying decision conditions (Balusa & Gorai, 2019).

Existing FAHP applications in mining, however, have predominantly focused on mining method selection, hazard prioritization, and risk assessment (Kar et al., 2024; Petroutsatou et al., 2024), with comparatively limited attention to rehabilitation strategy selection. Rehabilitation decisions require the simultaneous consideration of geotechnical risks, production panel availability, operational continuity, implementation feasibility, and cost-related trade-offs within an active underground mining environment. Furthermore, a common methodological limitation of AHP applications is the selection of evaluation criteria primarily based on expert familiarity rather than an explicitly articulated, value-based decision structure. Value-Focused Thinking (VFT) addresses this limitation by identifying and structuring the fundamental objectives and values of decision-makers before generating and evaluating alternatives (Keeney, 1996). VFT has been widely applied to complex decision-making problems involving multiple stakeholders and competing objectives (Parnell et al., 2013) and has also been integrated with AHP to facilitate structured group decision-making (Logullo et al., 2022). Accordingly, this study develops a systematic decision-support framework for rehabilitation strategy selection at the Alpha Block Cave (ABC) underground mine by integrating stakeholder analysis, Kepner–Tregoe Problem Analysis (KTPA), VFT, FAHP, and scenario-based sensitivity analysis. Specifically, the study addresses three research questions: (1) What are the key decision criteria, and what is their relative importance in rehabilitation decision-making under uncertainty? (2) How can an MCDM framework incorporating FAHP facilitate more systematic and transparent prioritization of rehabilitation strategies? (3) How robust is the preferred rehabilitation strategy under alternative operational priority scenarios? The scope of this study is limited to strategic rehabilitation decision-making and does not encompass production system redesign or the detailed engineering design of ground support systems.

METHOD

This study adopted a pragmatist research philosophy to develop a practical decision-support framework for rehabilitation challenges at the Alpha Block Cave (ABC) underground mine. An abductive approach was employed to integrate established multi-criteria decision-making (MCDM) concepts with empirical insights. The research used a mixed-methods design within an exploratory case study, primarily adopting a cross-sectional approach supplemented by retrospective operational records. As illustrated in Figure 1, the conceptual framework integrated stakeholder analysis and Kepner–Tregoe Problem Analysis (KTPA) to identify key rehabilitation challenges, followed by Value-Focused Thinking (VFT) to establish decision objectives and evaluation criteria. These criteria were subsequently incorporated into the Fuzzy Analytic Hierarchy Process (FAHP) to determine their relative weights and prioritize rehabilitation strategies. Finally, sensitivity analysis was conducted to assess the robustness of the preferred strategy under varying operational priorities.

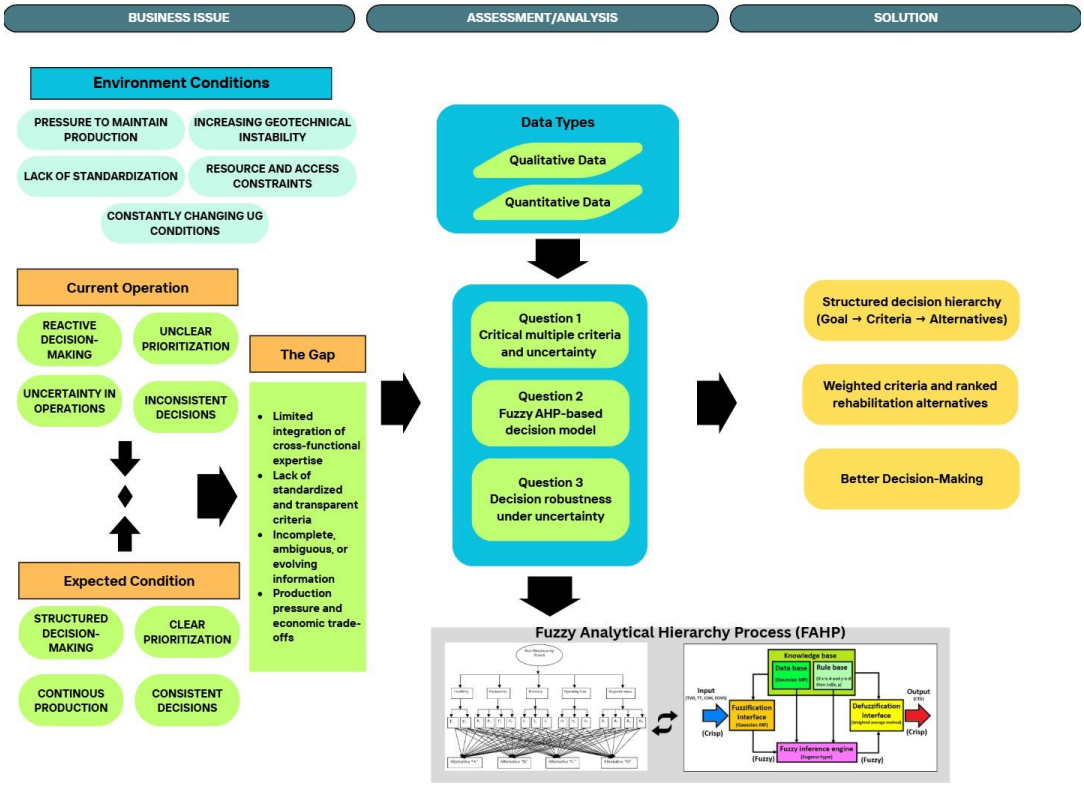


Figure 1. Conceptual Framework

Source: Authors.

Three data sources were used in this study. First, semi-structured interviews were conducted to examine existing decision-making practices, sources of uncertainty, stakeholder roles, and factors influencing rehabilitation prioritization. Participants were selected through purposive sampling based on their decision-making authority and operational expertise (Palinkas et al., 2015), informed by a stakeholder power–interest analysis (Bryson, 2004). Second, expert elicitation questionnaires were administered to obtain pairwise comparison judgments for criteria, subcriteria, and alternatives using Saaty's 1–9 fundamental comparison scale. Third, secondary data, including ground control inspection reports, hazard maps, rehabilitation backlogs, production forecasts, and governance procedures, were reviewed to validate stakeholder perspectives and contextualize the findings while maintaining confidentiality. Interview data were analyzed thematically following the procedures outlined by Braun and Clarke (2006).

The Fuzzy Analytic Hierarchy Process (FAHP) model was structured hierarchically, comprising the rehabilitation strategy prioritization goal, primary criteria, subcriteria, and decision alternatives. The analysis followed Buckley's (1985) fuzzy geometric mean method. Before fuzzification, the consistency of each pairwise comparison matrix was evaluated using the consistency index (CI) and consistency ratio (CR). Judgments were considered acceptable when the CR was below 0.10 (Saaty, 1977), as expressed in the following equations:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}, \quad \mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{1}$$

Each crisp judgment was then converted into a triangular fuzzy number (TFN) ã = (l, m, u) representing the lower, most likely, and upper values, using the scale in Table 2, so that each pairwise matrix became a fuzzy matrix Ã = [ãij].

Table 2. Triangular Fuzzy Number Conversion Scale

Crisp AHP value	Linguistic description	TFN (l, m, u)	Reciprocal TFN (1/u, 1/m, 1/l)
1	Equal importance	(1, 1, 2)	(1/2, 1, 1)
2	Weak/slight importance	(1, 2, 3)	(1/3, 1/2, 1)
3	Moderate importance	(2, 3, 4)	(1/4, 1/3, 1/2)
4	Moderate plus	(3, 4, 5)	(1/5, 1/4, 1/3)
5	Strong importance	(4, 5, 6)	(1/6, 1/5, 1/4)
6	Strong plus	(5, 6, 7)	(1/7, 1/6, 1/5)
7	Very strong importance	(6, 7, 8)	(1/8, 1/7, 1/6)
8	Very, very strong	(7, 8, 9)	(1/9, 1/8, 1/7)
9	Extreme importance	(8, 9, 9)	(1/9, 1/9, 1/8)

Source: Processed by the authors (2026).

The judgments of the ten experts were aggregated into a single group judgment for each pairwise comparison using the geometric mean, which preserves the ratio structure of the comparisons and is preferred to an arithmetic average because expert judgments are expressed as ratios, where R1, …, Rn are the individual comparison results of the n respondents:

$$\hat{r} = (R_1 \cdot R_2 \cdot \ldots \cdot R_n)^{\frac{1}{n}} \quad (2)$$

For each criterion i, the fuzzy geometric mean of the row r̃i and the fuzzy weight w̃i were then calculated as follows:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ldots \otimes \tilde{a}_{in})^{\frac{1}{n}} \quad (3)$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n)^{-1} \quad (4)$$

Finally, each fuzzy weight w̃i = (li, mi, ui) was defuzzified using the Center of Area (COA) method and normalized to obtain the local weight Wi, and global priorities were obtained by multiplying each local sub-criterion weight by the weight of its parent criterion:

$$w_i = \frac{l_i + m_i + u_i}{3}, \quad W_i = \frac{w_i}{\Sigma w_i} \quad (5)$$

Scenario-based sensitivity analysis was then applied to the level-1 criteria weights to test whether plausible shifts in managerial emphasis, such as a production-driven environment, deteriorating ground conditions, or tighter budget discipline, would alter the ranking of alternatives (Balusa & Gorai, 2019).

RESULTS AND DISCUSSION

Stakeholder Analysis and Respondent Selection

A power–interest matrix, constructed through a structured questionnaire, was used to classify the stakeholder groups involved in rehabilitation decisions (Bryson, 2004). As shown in Table 3, the Geotechnical/Ground Control, Production Strategic, and Underground Engineering groups are positioned in the high-power and high-interest quadrant and should be managed closely as key actors. Rehabilitation Operations has above-average power but relatively lower interest and should be kept satisfied, whereas Constructions shows high interest but lower power and should

be kept informed. The matrix served as an initial screening rather than as the formal sampling method.

Table 3. Stakeholder Power–Interest Levels

No	Stakeholder group	Power	Interest	Category
1	Geotechnical/Ground Control	3.81	4.31	Manage closely
2	Development Operations	3.17	3.00	Monitor
3	Rehabilitation Operations	3.67	3.17	Keep satisfied
4	Production Strategic	3.38	3.81	Manage closely
5	Underground Engineering	3.35	3.65	Manage closely
6	Constructions	2.50	3.75	Keep informed
	Average	**3.31**	**3.65**	

Source: Processed by the authors (2026).

Because AHP requires judgments from people who understand the problem and are directly involved in the decision, ten respondents were then purposively selected based on their direct involvement in assessing, recommending, reviewing, approving, or implementing rehabilitation activities (Palinkas et al., 2015). Random sampling was not appropriate because individuals not directly involved may lack sufficient knowledge of the decision context. The respondent profile is presented in Table 4.

Table 4. Respondent Profile

No	Role	Experience	Relevance
1–2	Superintendent Geotechnical Engineer; Senior Geotechnical Engineer	≥ 15; ≥ 12 years	Stability assessment of panels; interprets uncertainty and defines rehabilitation triggers; validates the risk side of the criteria and closure thresholds
3	Superintendent Development Operations	≥ 15 years	Manages day-to-day operations delivery; explains consequences of restricting high-capacity panels and practical constraints
4–6	Superintendent Rehab; General Foreman Rehab; Technical Expert Rehab	≥ 20; ≥ 15; ≥ 15 years	Owns execution feasibility of rehabilitation work; provides inputs on capacity, constraints, and achievable closure windows
7	General Foreman Strategic Operations	≥ 10 years	Integrates safety, production, and cost objectives and arbitrates trade-offs in cross-functional meetings
8–9	Chief Engineer Production; Chief Engineer Rehab	≥ 15 years	Translates closure decisions into production impacts and feasible schedules; defines work packages and planning assumptions
10	Chief Engineer Constructions	≥ 15 years	Manages construction activities, infrastructure readiness, and implementation support

Source: Processed by the authors (2026).

Problem Analysis and Value-Focused Thinking

The Kepner–Tregoe analysis (Table 5) indicates that the rehabilitation issue is not caused solely by ground deterioration or resource limitations, which are inherent conditions of underground mining. The underlying business-process issue is the absence of a consistently

applied cross-functional mechanism for integrating ground condition, production consequences, implementation feasibility, and economic considerations into rehabilitation prioritization. This weakness becomes more visible when panel availability is limited, deterioration progresses rapidly, and resources are constrained, leading to greater reliance on case-by-case discussion, repeated alignment, decision revision, or delayed intervention.

Table 5. Kepner–Tregoe Problem Analysis

Dimension	Is	Is not	Distinction	Likely cause
What	Rehabilitation decisions are inconsistent and slow	Not a routine single-function decision	Multi-stakeholder, high-risk decision	Unclear decision criteria/process
Where	ABC production panels	Not mainly non-production areas	Safety risk and production value conflict	Different stakeholder priorities
When	Fast-changing conditions, low panel availability, high production pressure	Less visible during stable operations	Worse when availability is below target	Time pressure and uncertainty
Extent	Deferrals, revisions, and escalations are increasing	Not stable or improving	Indicates a systemic issue	Criteria, data alignment, and governance gaps

Source: Processed by the authors (2026).

While KTPA clarifies what is going wrong, it does not define what the decision should achieve. VFT was therefore used to shift the analysis from problem diagnosis to goal definition (Keeney, 1996). Figure 2 presents the resulting objectives hierarchy, in which attributes identified with stakeholders are linked to means objectives and to the fundamental objective of improving rehabilitation prioritization. Combined with factors commonly considered in rehabilitation decisions, such as ground condition, resource requirements, production impact, and cost (Tasse et al., 2020; Todd, 2007), this structure was translated into four criteria and eight sub-criteria for the FAHP hierarchy, as summarized in Table 6 (Logullo et al., 2022).

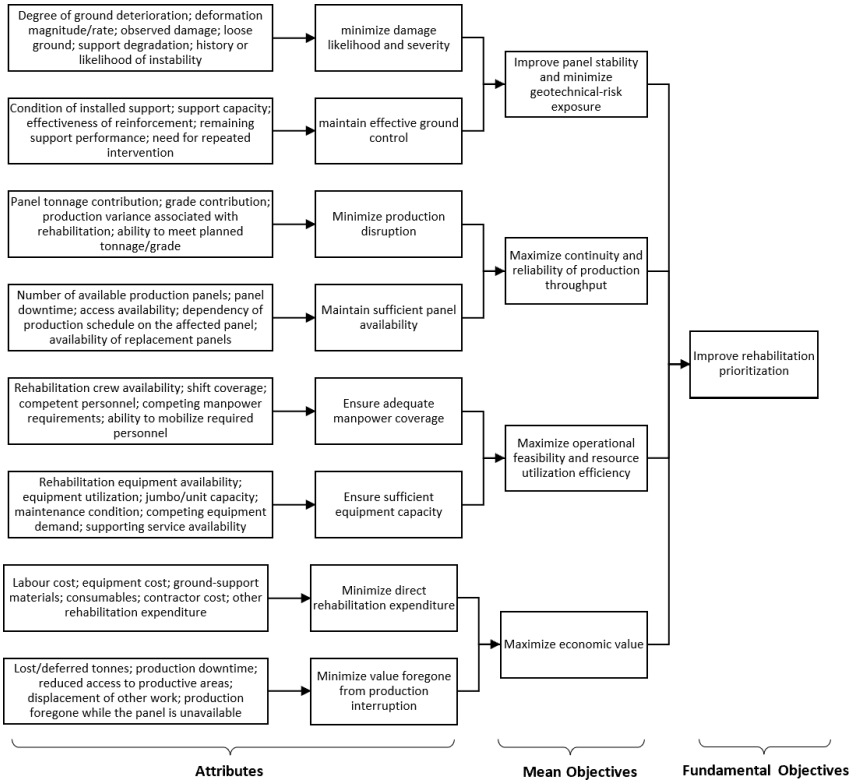


Figure 2. Objectives Hierarchy from Value-Focused Thinking

Source: Authors.

Table 6. Decision Criteria and Sub-criteria

Criterion (VFT objective)	Sub-criterion	Description
Ground Conditions & Stability, C1 (improve panel stability and reduce geotechnical-risk exposure)	Damage Likelihood/Severity (S1)	Extent to which deterioration, deformation, support degradation, or instability is likely to occur and how severe its consequences may be
	Ground Control Effectiveness (S2)	Adequacy of support and control measures to maintain stability and sustain safe access
Production Impacts, C2 (maximize continuity and reliability of production throughput)	Tonnage/Grade Achievement (S3)	Effect of a rehabilitation decision on planned tonnage and ore grade performance
	Panel Availability (S4)	Extent to which sufficient productive panels remain available during rehabilitation
Operational Feasibility, C3 (maximize feasibility and resource utilization efficiency)	Manpower Coverage (S5)	Adequacy of crews, deployment capability, and execution readiness
	Units Capacity (S6)	Adequacy of equipment, machinery, tools, and supporting capacity
Cost Effectiveness, C4 (maximize economic value by balancing rehabilitation cost and production impact)	Direct Costs (S7)	Immediate costs such as labor, materials, support installation, and equipment use
	Opportunity Costs (S8)	Economic value lost from reduced production, deferred extraction, or downtime

Source: Processed by the authors (2026).

Alternatives Generation

Following the VFT logic, alternatives were derived from the question of what feasible actions could better achieve the fundamental objectives under current operational constraints, through expert consultation and review of current practices. Three operationally realistic alternatives were formulated: Alternative 1 (A1), Parallel Rehabilitation via Resource Expansion, which increases manpower and equipment to rehabilitate multiple areas simultaneously; Alternative 2 (A2), Production Reallocation and Throughput Adjustment, which shifts production away from high-risk panels to more stable areas while temporarily adjusting throughput targets; and Alternative 3 (A3), the Operator Damage Prevention Program, which targets controllable sources of deterioration through improved visibility, targeted training, reinforcement of standard operating procedures, and traffic control to reduce avoidable equipment damage. The pros and cons identified by the experts are summarized in Table 7; they represent practical characteristics rather than predetermined conclusions about priority.

Table 7. Pros and Cons of the Alternatives

Alternative	Pros	Cons
A1. Parallel Rehabilitation via Resource Expansion	May accelerate rehabilitation progress; allows several areas to be addressed concurrently; may reduce prolonged exposure in deteriorated areas	Requires additional manpower and equipment; may increase underground congestion; higher resource and cost requirements
A2. Production Reallocation & Throughput Adjustment	May create rehabilitation windows; reduces reliance on affected panels; provides flexibility in sequencing rehabilitation	May reduce short-term throughput; requires production-plan adjustment; depends on alternative panel capacity
A3. Operator Damage Prevention Program	May reduce future damage by equipment; improves operating practices	Benefits are gradual, not immediate; requires cultural and behavioral change

Source: Expert interviews processed by the authors (2026).

Consistency, Aggregation, and Defuzzification

The ten experts compared criteria, sub-criteria, and alternatives in pairs through an online questionnaire. As shown in Table 8, all consistency ratios were below the 10% threshold, indicating that the judgments were logically coherent and viable for the fuzzy procedure. The level-2 comparisons involve two sub-criteria per criterion and therefore yield a CR of 0%.

Table 8. Consistency Ratio Checks

Pairwise comparison	CR	Threshold	Remark
Level 1: criteria (C1–C4)	1.2%	< 10%	Acceptable
Level 2: sub-criteria (S1–S8)	0%	< 10%	Acceptable
Level 3: alternatives (A1–A3)	4.5%	< 10%	Acceptable

Source: Processed by the authors (2026).

After conversion into TFNs, the individual judgments were aggregated using the geometric mean. Table 9 presents the aggregated fuzzy decision matrix for the criteria, which shows that Ground Conditions & Stability (C1) is consistently judged more important than the other three criteria, particularly Cost Effectiveness (C4).

Table 9. Aggregated Fuzzy Decision Matrix for the Criteria

TFN (l, m, u)	C1	C2	C3	C4
C1	(1, 1, 1)	(2.95, 3.65, 4.55)	(1.57, 2.23, 2.89)	(4.14, 4.99, 5.69)
C2	(0.22, 0.27, 0.34)	(1, 1, 1)	(0.58, 0.72, 0.90)	(1.79, 2.30, 2.94)
C3	(0.35, 0.45, 0.64)	(1.11, 1.38, 1.74)	(1, 1, 1)	(2.68, 3.55, 4.36)
C4	(0.18, 0.20, 0.24)	(0.34, 0.43, 0.56)	(0.23, 0.28, 0.37)	(1, 1, 1)

Note: C1 = Ground Conditions & Stability; C2 = Production Impacts; C3 = Operational Feasibility; C4 = Cost Effectiveness. Source: Processed by the authors (2026).

The fuzzy geometric means and fuzzy weights were then defuzzified with the COA method and normalized into local weights, as shown in Table 10. Within each criterion, Damage Likelihood/Severity, Panel Availability, Manpower Coverage, and Direct Costs received the larger local weights.

Table 10. Defuzzification Results and Local Weights

Element	Geometric mean	Fuzzy weight	Defuzzified value	Local weight
C1	(2.09, 2.52, 2.94)	(0.36, 0.51, 0.71)	0.526	0.505
C2	(0.69, 0.82, 0.97)	(0.12, 0.17, 0.24)	0.173	0.166
C3	(1.01, 1.22, 1.48)	(0.17, 0.25, 0.36)	0.259	0.248
C4	(0.34, 0.40, 0.47)	(0.06, 0.08, 0.11)	0.084	0.081
S1	(1.12, 1.17, 1.21)	(0.53, 0.58, 0.62)	0.579	0.577
S2	(0.72, 0.81, 0.88)	(0.34, 0.39, 0.45)	0.424	0.423
S3	(0.72, 0.81, 0.88)	(0.34, 0.39, 0.45)	0.396	0.389
S4	(1.14, 1.24, 1.39)	(0.54, 0.61, 0.71)	0.623	0.611
S5	(1.07, 1.13, 1.19)	(0.51, 0.56, 0.61)	0.561	0.562
S6	(0.84, 0.88, 0.93)	(0.39, 0.43, 0.47)	0.437	0.438
S7	(1.58, 1.72, 1.79)	(0.75, 0.85, 0.92)	0.842	0.743
S8	(0.55, 0.58, 0.63)	(0.26, 0.28, 0.32)	0.292	0.257

Source: Processed by the authors (2026).

Criteria Weights and Final Priority Ranking

The final criterion weights show that the rehabilitation strategy decision is primarily driven by Ground Conditions & Stability (50.97%), followed by Operational Feasibility (24.71%), Production Impacts (16.30%), and Cost Effectiveness (8.02%). Together, geotechnical and operational feasibility criteria account for 75.68% of the total weight, indicating that the preferred strategy must be not only technically sound but also executable under real operating constraints. Table 11 presents the global priority of each sub-criterion and the performance of the alternatives. Damage Likelihood/Severity (29.5%) and Ground Control Effectiveness (21.4%) together account for more than half of the total weight, followed by a group of moderately influential sub-criteria, namely Manpower Coverage (13.9%), Units Capacity (10.8%), and Panel Availability (10.0%), which jointly represent 34.7%. Tonnage/Grade Achievement (6.3%), Direct Costs (6.0%), and Opportunity Costs (2.0%) received the lowest weights.

Table 11. Global Priorities and Final Ranking of Alternatives

Criterion (weight)	Sub-criterion (local weight)	Global priority	A1	A2	A3
Geotechnical (0.510)	Damage Likelihood/Severity (0.580)	29.5%	25.8%	54.4%	19.8%
	Ground Control Effectiveness (0.420)	21.4%	71.1%	19.6%	9.4%
Production (0.163)	Tonnage/Grade Achievement (0.389)	6.3%	25.3%	65.0%	9.7%
	Panel Availability (0.611)	10.0%	69.5%	22.0%	8.5%
Resources (0.247)	Manpower Coverage (0.562)	13.9%	8.6%	23.1%	68.3%
	Units Capacity (0.438)	10.8%	10.0%	26.4%	63.6%
Cost (0.080)	Direct Costs (0.746)	6.0%	7.5%	28.1%	64.4%
	Opportunity Costs (0.254)	2.0%	9.4%	61.5%	29.1%
Overall		**100%**	**34.30%**	**35.58%**	**30.13%**
Ranking			**2nd**	**1st**	**3rd**

Note: A1 = Parallel Rehabilitation via Resource Expansion; A2 = Production Reallocation & Throughput Adjustment; A3 = Operator Damage Prevention Program. Source: Processed by the authors (2026).

These results indicate that rehabilitation decision-making is driven primarily by operational risk and continuity rather than direct cost minimization. The low weight of cost does not mean that experts consider financial factors unimportant; rather, cost functions as a supporting criterion, because the loss of one production panel in a productive, high-grade area could cost the company approximately USD 1 million per day in potential revenue. Maintaining panel stability and avoiding production disruption may therefore create greater business value than choosing the least expensive method. The dominance of damage likelihood and ground control effectiveness is meaningful in underground mining because damage progression and ineffective ground control directly affect access, infrastructure integrity, panel operability, and production continuity. The moderate weight of manpower, equipment, and panel availability shows that a technically desirable option may still fail if it cannot be supported by sufficient resources or timely access, which is consistent with the time-sensitive and resource-dependent nature of rehabilitation (Potvin & Wesseloo, 2013; Tasse et al., 2020). Conversely, the comparatively low weights of tonnage/grade achievement and direct and opportunity costs suggest that the model does not treat production output or immediate economic efficiency as the primary basis for selecting a strategy; these factors are instead regarded as outcomes to be protected through stronger control of technical risk and better execution capability. This weighting pattern reflects a value-based logic in which the main objective is not to minimize rehabilitation expenditure in isolation, but to prevent larger losses arising from reactive or delayed rehabilitation decisions.

At the alternative level, A2 ranks first (35.58%), but its margin over A1 (34.30%) is small, so A2 is not a runaway winner but the option that gives the best balance under the current weighting structure. A2 performs very strongly on damage likelihood (54.4%) and tonnage/grade achievement (65.0%), which makes it the strategy most aligned with an operation that must control deterioration while protecting output. A1 remains highly competitive, being strongest on ground control effectiveness (71.1%) and panel availability (69.5%), and may be more attractive when maintaining sufficient active and accessible panels is a key concern because increased rehabilitation capacity can return affected panels to service sooner. A3 performs best on manpower coverage (68.3%), units capacity (63.6%), and direct costs (64.4%), making it the most practical and cost-efficient option, but these dimensions carry less weight than geotechnical risk in the baseline model. Overall, the FAHP framework turns a complex and uncertain problem into a transparent and repeatable prioritization process that combines technical, operational, production, and cost considerations while capturing variation in expert judgment, in line with the role of fuzzy MCDM in mining decisions (Bajić et al., 2020; Balusa & Gorai, 2021; Sitorus et al., 2019).

Sensitivity Analysis

Because the final ranking is influenced by the weighting assumptions, scenario-based sensitivity analysis was applied to the level-1 criteria weights (Table 12). Scenario 1 assumes that management directs an increase in production throughput while rehabilitation resources remain unchanged, raising the production weight from 16.3% to 23%. Scenario 2 assumes that operating conditions deteriorate beyond expectations, increasing the number of areas requiring rehabilitation while throughput must be maintained, so the geotechnical (55%) and resource (29%) weights

increase. Scenario 3 assumes a tighter budget environment requiring stricter cost and resource discipline while minimum throughput is preserved, raising the cost weight from 8.0% to 15%.

Table 12. Scenario-Based Sensitivity Analysis

Item	Baseline	Scenario 1	Scenario 2	Scenario 3
Criteria weights				
Geotechnical	51.0%	47%	55%	43%
Production	16.3%	23%	10%	15%
Resources	24.7%	20%	29%	27%
Cost	8.0%	10%	6%	15%
Priority of alternatives				
A1. Parallel Rehabilitation	34.30%	35.7%	33.0%	30.8%
A2. Production Reallocation	35.58%	36.2%	35.1%	35.0%
A3. Damage Prevention Program	30.13%	28.1%	31.9%	34.2%

Source: Processed by the authors (2026); priorities converted from the original bar chart.

A2 remained the highest-ranked option in all scenarios, indicating that the preferred solution is not highly sensitive to moderate changes in criteria weighting, although the margin narrowed under certain conditions (Balusa & Gorai, 2019). In Scenario 1, A1 became more competitive (35.7% versus 36.2%), showing that panel readiness and ground control become more important when throughput expectations rise. In Scenario 2, A2 remained clearly preferred (35.1%), suggesting that it is stable under technically demanding conditions. In Scenario 3, A3 improved significantly (34.2%), reflecting its strength in resource efficiency and cost. The framework is therefore not overly rigid; it captures realistic trade-offs and supports adaptive decision-making under different operating conditions.

Taken together, the findings answer the three research questions, as summarized in Table 13. The value of the framework lies not only in identifying the preferred strategy but also in explaining why it is preferred, under what conditions the recommendation remains stable, and when other alternatives may become more attractive. In this sense, the proposed approach is a decision-support mechanism that complements existing technical assessment and managerial judgment rather than replacing current expertise, and its outputs should be read together with mandatory safety and geotechnical requirements.

Table 13. Answers to the Research Questions

Research question	Answer from the study	Evidence/output
RQ1: What are the key decision criteria and their relative importance in rehabilitation decision-making under uncertainty in the ABC mine?	Geotechnical Conditions, Operational Feasibility, Production Impacts, and Cost Effectiveness, in that order of importance	FAHP criteria weights
RQ2: How can a systematic multi-criteria framework incorporating FAHP support more structured prioritization of rehabilitation strategies?	FAHP converts expert judgment into transparent weights and rankings	Global priority ranking
RQ3: How robust is the preferred strategy under alternative operational priority scenarios?	Alternative 2 is robust as the baseline choice, but margins shift under different scenarios	Scenario-based sensitivity analysis

Source: Processed by the authors (2026).

Implementation Plan

The implementation of the framework is structured using the Plan-Do-Check-Act cycle (Table 14). Mandatory safety, geotechnical, and regulatory requirements should be assessed before feasible rehabilitation responses are evaluated using FAHP, and each pilot case records the evidence, evaluation results, final management decision, and reasons for any deviation from the model recommendation. The Check phase compares pilot performance with the baseline in terms of adoption rate, decision lead time, documentation completeness, decision revision, recommendation acceptance, usability, and ranking stability, not to attribute all operational improvements to the framework but to determine whether it improves the structure, transparency, and repeatability of decisions.

Table 14. Implementation Plan Based on the Plan-Do-Check-Act Cycle

Phase	Key action	Expected output	Accountable function
Plan	Align stakeholders and confirm implementation scope	Approved scope, project owner, participating functions, and schedule	Underground Management / Project Sponsor
Plan	Validate the framework and establish baseline	Confirmed criteria, alternatives, screening requirements, pilot cases, and baseline KPIs	Geotechnical, Operations, Rehabilitation, and Planning
Plan	Develop the operational tool and guidance	Ready-to-use FAHP tool, input form, screening checklist, and decision template	Technical Services / Planning Engineer
Do	Train key users	Users understand the framework, process, and decision responsibilities	Senior Engineers / Planning Team
Do	Conduct a controlled pilot	Framework applied to 3–5 representative rehabilitation cases with documented results	Geotechnical, Operations, Rehabilitation, and Planning
Check	Evaluate pilot performance	Results compared with baseline, including usability, decision time, documentation quality, and recommendation stability	Cross-Functional Review Team
Act	Refine and approve the framework	Updated framework and management approval for controlled operational use	Framework Owner / Underground Management
Act	Integrate into routine decision-making	Framework embedded in regular rehabilitation planning and review meetings	UG Planning Superintendent / Operations Coordination
Check	Monitor early implementation	Monthly performance dashboard and management review	Project Lead / Underground Management

Phase	Key action	Expected output	Accountable function
Act	Standardize and continuously improve	Final framework, assigned owner, approved procedure, and periodic review cycle	Underground Management / Senior Engineers

Source: Processed by the authors (2026)

CONCLUSION

This study developed a structured decision-support framework for prioritizing rehabilitation strategies at the Alpha Block Cave underground mine under conditions of uncertainty, competing operational priorities, and cross-functional complexity. The findings revealed that the primary challenge was the absence of a shared, transparent, and criteria-based decision-making framework rather than a purely technical issue. The Fuzzy Analytic Hierarchy Process (FAHP) results identified Geotechnical Conditions as the most influential criterion (50.97%), followed by Operational Feasibility (24.71%), Production Impacts (16.30%), and Cost Effectiveness (8.02%). Damage Likelihood/Severity (29.54%) and Ground Control Effectiveness (21.43%) emerged as the most influential subcriteria, reflecting a risk-oriented approach emphasizing ground stability. Production Reallocation and Throughput Adjustment achieved the highest baseline priority (35.58%), followed by Parallel Rehabilitation via Resource Expansion (34.30%) and the Operator Damage Prevention Program (30.13%). The preferred strategy maintained its highest ranking across all sensitivity scenarios, although Parallel Rehabilitation became more competitive under increased production pressure, while the Operator Damage Prevention Program gained importance under greater cost constraints. Based on these findings, management should adopt Production Reallocation and Throughput Adjustment as the preferred baseline strategy while maintaining flexibility to accommodate changing operational conditions. Parallel Rehabilitation should be reconsidered when panel readiness and ground control requirements become critical, whereas the Operator Damage Prevention Program should be implemented as a complementary preventive measure rather than a substitute for necessary corrective rehabilitation. Furthermore, the proposed evaluation criteria, scoring templates, and prioritization procedures should be integrated into routine cross-functional planning involving geotechnical, production, operations, rehabilitation, planning, and construction teams. Future research should assess the consistency of the proposed criteria, weights, and strategic preferences across stakeholder groups and other underground mining operations to strengthen the framework's external validity.

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CONFLICT OF INTEREST

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AUTHOR CONTRIBUTION

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GENERATIVE ARTIFICIAL INTELLIGENCE USAGE STATEMENT

The authors state that no generative artificial intelligence was used in the preparation of this article.

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