

Article

Prioritization of Critical Sustainability Factors in Medium-Scale Mining: The Coquimbo Region Case

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Abstract

This study aims to identify and rank the critical factors influencing the sustainability of medium-scale mining in the Coquimbo Region, Chile. To address this decision problem, the Analytic Hierarchy Process (AHP) was applied using Expert Choice software (Comparion® version 11) to structure and prioritize economic, social, and environmental criteria within the decision model. The analysis was based on an expert panel comprising 14 senior professionals from the regional mining industry. Their expert judgment was elicited through structured pairwise comparison questionnaires, consistent with the AHP model. The aggregation of judgments enabled the derivation of weights and the corresponding priority vector, ensuring a rigorous prioritization process. The model results indicate that the “Environmental” and “Social” criteria achieved the highest relative weights (42.9% each), significantly exceeding the “Economic” criterion (14.3%). At the level of alternatives, “Identify Emission Sources and Environmental Risks” attained the highest global priority (5.3%). However, the sensitivity analysis reveals that alternatives associated with the sub-criterion “Air Pollution” demonstrate greater model robustness under variations in weights, maintaining dominant positions across multiple scenarios. From an applied perspective, these findings support resource allocation and the formulation of sustainability strategies in mining operations by prioritizing actions with greater impact and stability, particularly in atmospheric emissions management and community engagement. This contributes to improving environmental performance and strengthening the social acceptance of mining operations. Overall, the study provides a robust methodological framework that enhances strategic decision-making in complex mining contexts.

Keywords: decision-making; Analytic Hierarchy Process; sustainability; medium-scale mining; multicriteria analysis; mining sustainability



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1. Introduction

Chile, one of the world’s leading copper producers, has relied on mining as a fundamental pillar of its economy since the late nineteenth century. This sector, which includes some of the largest copper mines globally, supplies essential minerals for goods and services required for the transition toward a low-carbon future [1]. However, persistent concerns regarding the economic, social, and environmental impacts of mining activities continue to undermine public trust in their capacity to generate benefits beyond resource extraction [2].

Mining activities generate multiple negative impacts, including biodiversity loss [3], soil and water contamination [4], excessive water consumption [5], and adverse effects on the health of workers and nearby communities [6]. In response, mining companies must implement

sustainability strategies grounded in empirical evidence, promoting responsible management that integrates economic profitability, social equity, and environmental responsibility.

Sustainable development in mining requires mitigating impacts on water, air, soil, landscapes, and communities. In addition to increasing demand for metals and escalating environmental challenges, the industry faces growing social pressure to guarantee the rights of Indigenous peoples and local communities [7]. Therefore, identifying and prioritizing the critical factors affecting sustainability is essential for strategic development and social acceptability.

Global pressure to ensure a sustainable supply of critical minerals, particularly copper, has intensified the need to redefine mining strategies beyond traditional profitability-focused approaches. Copper demand is projected to increase by 275% to 350% by 2050 [8], posing significant challenges in terms of operational sustainability and resource availability. This scenario implies not only the expansion of extractive activities into more complex and ecologically fragile environments but also the intensification of socio-environmental conflicts [2,7].

At both global and national levels, mining-driven economic growth has been accompanied by persistent challenges, including water and air pollution, ecosystem degradation, and impacts on community health [3,4,6]. These issues have increased pressure from society and regulatory bodies to transition toward more sustainable development models [9,10]. Such pressures are further compounded by rising operational costs, declining productivity, and stricter environmental and social regulations, which threaten the long-term competitiveness of the sector [5,11].

In this context, identifying and prioritizing critical sustainability factors becomes an operational necessity. The literature indicates that the absence of structured frameworks limits the integration of economic, social, and environmental dimensions in complex decision-making processes [12,13]. This limitation reduces the ability of companies to allocate resources efficiently, design effective mitigation strategies, and anticipate socio-environmental risks. Consequently, tools that support prioritization and enable the evaluation of decision stability under changing conditions are essential for improving sustainable performance.

Effective mining management requires continuous monitoring, adaptive responses, and periodic evaluation of impacts and social transformations [2]. Given its influence on public policy, fiscal revenues, social welfare, and the environment, the sector is subject to strict oversight and demands rigorous analytical approaches to support sustainable decision-making [11].

The pursuit of sustainable development represents a major challenge for mining. All Sustainable Development Goals (SDGs) are compatible with mining activities [9], and at least 11 of the 17 SDGs are significantly linked to the sector, either positively or negatively [10].

In the Coquimbo Region, medium-scale mining constitutes the primary productive activity, providing economic stability and occupying a strategic niche through the exploitation of deposits not targeted by large-scale mining. This segment is characterized by selective operations, higher ore grades, and the capacity to generate local opportunities [14]. Its contribution is substantial, with copper production comparable to that of countries such as Poland, the 14th largest global producer, generating sales exceeding USD 3.588 billion in 2021 and employing approximately 24,000 people [15].

With the advancement of environmental, social, and governance (ESG) criteria, regulatory requirements have intensified, posing significant economic challenges for the sector. If not adequately addressed, these requirements may compromise the ability of medium-scale mining to sustain its operational levels [16].

In this context, multi-criteria decision-making (MCDM) methods have gained increasing relevance for alternative evaluation and comparative analysis. These methods have been widely applied across sectors [12] and, in mining, have primarily addressed strategic and operational problems [17,18].

Among these approaches, the AHP, developed by Saaty (1980) [19], is a widely used multi-criteria decision-making method for prioritizing complex decisions and integrating economic, social, and environmental criteria. Its simplicity, theoretical robustness, and ability to assess inconsistency in judgments make it particularly suitable for industrial applications [20–22]. AHP is often preferred due to its strong theoretical foundation and its capacity to directly measure inconsistency in respondents' judgments [19].

Accordingly, the application of multi-criteria decision-making methods such as the AHP is essential to support strategic decision-making in mining. By providing a structured framework for evaluating and comparing sustainability criteria, these methods enhance decision effectiveness.

Although AHP has been applied in regional mining contexts—such as water resource management [23], selection of loading and hauling equipment suppliers [24], and selection of explosives suppliers [25]—these studies focus on specific decision problems and do not address the comprehensive prioritization of critical factors affecting the sustainability of medium-scale mining.

In this context, and considering the limitations identified in the literature, the following research question arises: what are the critical factors that determine the sustainability of medium-scale mining in the Coquimbo Region, and how can they be consistently ranked to support strategic decision-making? It is hypothesized that the application of a structured multi-criteria decision-making approach, such as the Analytic Hierarchy Process (AHP), enables the identification of these factors and the evaluation of their stability under variations in weights, thereby providing a more robust basis for sustainable sector management.

Therefore, this study aims to identify and rank the critical factors affecting the sustainability of medium-scale mining in the Coquimbo Region. To this end, the AHP is applied using Expert Choice software (Comparion® version 11), providing a robust tool to support the reorientation of mining strategies toward more sustainable practices aligned with current societal expectations.

The remainder of the paper is organized as follows. Section 2 presents the methodological framework for multi-criteria decision-making, including the fundamentals of AHP. Section 3 describes the construction of the hierarchical structure, including the definition of criteria and subcriteria and the data collection process. Section 4 presents and discusses the model results, including reliability analysis using Cronbach's alpha, the consistency index (CI), global priority, and sensitivity analysis. Finally, Section 5 presents the conclusions, limitations, and future research directions.

2. Multi-Criteria Analysis in Decision-Making

The problem analyzed in this research involves multiple evaluation criteria, situating it within the domain of MCDM, where economic, social, and environmental factors are simultaneously considered and assessed through both qualitative and quantitative judgments. Among the available MCDM methods, the AHP was selected due to its capacity to structure complex decision problems, integrate tangible and intangible criteria, and evaluate the consistency of pairwise comparison.

The AHP is a widely applied multi-criteria decision-making method for evaluating complex, multi-attribute problems involving both quantitative variables and qualitative judgments [13,26]. In the mining industry, it has demonstrated effectiveness in modeling both strategic and operational scenarios [27]. Its selection in this study is based not only on

its widespread application but also on its methodological suitability. AHP structures the decision problem through a hierarchical structure composed of goals, criteria, subcriteria, and alternatives, enabling a systematic and transparent analysis [19,28]. Its ability to integrate quantitative and qualitative information is particularly relevant in mining contexts, where decisions involve technical variables, expert judgment, and social considerations.

Unlike other MCDM methods, AHP explicitly evaluates the consistency of judgments through the consistency ratio (CR), thereby strengthening the reliability of the model results [20,29]. Furthermore, its participatory approach facilitates the incorporation of expert judgment, transforming subjective evaluations into quantifiable priorities. The inclusion of sensitivity analysis enables the assessment of model robustness under variations in weights, addressing a key gap in the literature related to the integration of prioritization and robustness analysis. Therefore, AHP not only supports the identification and ranking of critical factors in medium-scale mining but also contributes to addressing this methodological gap [12,13,30].

In this study, AHP enables the evaluation and prioritization of alternatives that balance economic, social, and environmental dimensions, thereby contributing to sustainability in the sector. This approach provides a practical tool for aligning mining practices with contemporary sustainability requirements.

Within AHP, the decision problem is structured into hierarchical levels comprising the goals, criteria, subcriteria, and alternatives. Following the definition of the hierarchical structure, elements at each level are evaluated through pairwise comparisons conducted by an expert panel. These evaluations are used to construct pairwise comparison matrices, from which the relative importance of each element is derived. Matrix algebra is subsequently applied to obtain the priority vector, enabling a systematic evaluation of alternatives based on expert judgment [28]. This process employs values from the fundamental scale (Saaty scale), typically ranging from 1 to 9, to estimate dominance, or alternatively relies on pairwise dominance ratios derived from empirical measurements [31].

The objective of this method is to identify a set of alternatives that maximizes the sum of global priorities, addressing the fundamental question posed by Saaty et al. [32]: which combination of alternatives yields the highest overall priority?

Despite its advantages, AHP presents limitations that must be considered when interpreting the model results. First, the method relies on expert judgment, introducing inherent subjectivity into the decision model. Evaluations depend on the experience, intuition, and perception of decision-makers and may be influenced by individual biases and contextual factors. Additionally, the cognitive burden associated with numerous pairwise comparisons may lead to fatigue and affect response quality. However, AHP does not eliminate subjectivity; rather, it renders it explicit, comparable, and verifiable through consistency verification using the consistency index (CI), thereby enhancing reliability of results [19].

Second, AHP assumes independence among criteria and alternatives, which may not fully capture the interdependent nature of real-world systems, particularly in mining contexts where economic, social, and environmental variables interact. This assumption simplifies the hierarchical structure and may limit the representation of the decision problem. Extensions such as the Analytic Network Process (ANP) or fuzzy AHP have been proposed to address interdependencies and uncertainty in complex systems.

Finally, the phenomenon of rank reversal may occur, whereby the addition or removal of alternatives alters the established ranking. This effect is associated with the sensitivity of results to variations in weights, where small changes can significantly affect the global priority and reveal potential stability issues. In this study, this limitation is mitigated through the consistent definition of alternatives and the application of sensitivity analysis, which

enables the identification of critical thresholds and the evaluation of model robustness. This approach strengthens the interpretation and validity of the model results within the analyzed context.

Despite these limitations, AHP constitutes a methodologically appropriate approach for this study, as it enables the structuring, prioritization, and evaluation of the stability of critical sustainability factors in complex contexts, thereby effectively addressing the research objective and the identified gap in the literature.

AHP Fundamentals

AHP relies on pairwise comparisons of elements at the same hierarchical level with respect to a higher-level element, which serves as the evaluation criterion. These comparisons determine both the relative importance of each element and the intensity of preference. The Saaty scale quantifies this judgment, assigning values from 1 (equal importance) to 9 (extreme importance of one element over another), thereby converting subjective assessments into numerical form [19].

Pairwise comparisons produce a square matrix $A = [a_{ij}]$, where each element a_{ij} represents the relative importance of element i with respect to element j and satisfies the reciprocal property $a_{ij} = 1/a_{ji}$. The general form of this matrix is shown in Equation (1):

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn} \end{pmatrix} \quad (1)$$

The AHP procedure continues with the normalization of the pairwise comparison matrix and the calculation of relative weights for each element. These weights are derived from the priority vector associated with the maximum eigenvalue of the matrix, λ_{max} , as expressed in Equation (2):

$$A_w = \lambda_{max} \times w \quad (2)$$

In the ideal case of perfect consistency, matrix A has a rank of one and $\lambda_{max} = n$, allowing weights to be obtained by normalizing any row or column of the matrix.

The reliability of AHP results depends on the coherence of expert judgments during the pairwise comparison process. Consistency is evaluated using the consistency index (CI), defined in Equation (3):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

CI is compared with the random index (RI) to assess the acceptability of the judgment matrix. This comparison verifies the logical coherence of expert evaluations and, consequently, the reliability of the derived weights [33].

3. Construction of the Hierarchical Model

3.1. Classification of Criteria and Subcriteria

The first step in the methodology involved identifying the criteria, subcriteria, and alternatives, based on a comprehensive literature review on mining sustainability and multi-criteria decision-making. Table 1 presents the classification of criteria, subcriteria, alternatives, and sub-alternatives used to construct the hierarchical structure (Figure 1).

Table 1. Criteria, Subcriteria, and Alternatives.

Criteria	Code	Sub-Criteria	Code	Alternatives	Code	Sub-Alternatives	Code
Economic	A	Mining Business	A ₁	Preference for Sustainable Suppliers	A ₁₁		
				Business Competitiveness and Profitability	A ₁₂		
				Operation of Processes Without Freshwater Use	A ₁₃		
		Inequalities Reduction	A ₂	Community Influence in Decision-Making	A ₂₁		
				Wage Gap Between Staff and Contract Workers	A ₂₂		
				Increased Participation of Indigenous Workers	A ₂₃		
		Generation of Economic Activity	A ₃	Ensure Sustainable Income Over Time	A ₃₁		
				Provide Economic Opportunities Within the Community	A ₃₂		
				Promote SMEs in Mining Areas	A ₃₃		
		Transparent Management	A ₄	Transparent and Responsible Management of Water Resources	A ₄₁		
				Early Citizen Participation in Projects	A ₄₂		
				Avoid Undermining the Trust of External Organizations	A ₄₃		
		Regulatory Framework	A ₅	Lack of Monitoring of Environmental Regulations	A ₅₁		
				Establish Formal and Accessible Complaint and Reporting Mechanisms	A ₅₂		
				Respect the Free, Prior, and Informed Consent of Communities	A ₅₃		
Social	B	Gender Equality	B ₁	Increase Female Participation Through Targeted Recruitment Strategies	B ₁₁		
				Male Dominance in the Mining Sector	B ₁₂		
				Equal Pay Between Men and Women	B ₁₃		
				Promote More Women to Visible Leadership Positions	B ₁₄		
		Laboral Crisis	B ₂	Aging Workforce	B ₂₁		
				Shortage of Workers with In-Demand Technological Skills	B ₂₂		
				Industry Perceived as Unattractive by Younger Generations	B ₂₃		
		Health and Well-being	B ₃	Implementation of Occupational Health and Safety Programs	B ₃₁		
				Risk of Illness Due to Climatic Conditions	B ₃₂		
				Reduction in Occupational Illnesses and Fatalities	B ₃₃		
				Inclusion of People with Disabilities	B ₃₄		

Table 1. Cont.

Criteria	Code	Sub-Criteria	Code	Alternatives	Code	Sub-Alternatives	Code
Social	B	Development of Community Assets	B ₄	Development of Basic Services and Local Economy	B ₄₁		
				Expansion of Connectivity in Surrounding Communities	B ₄₂		
				Social Investments Directed Toward Communities	B ₄₃		
		Education and Training	B ₅	Development of Technical and Vocational Training Programs	B ₅₁		
				Lack of Opportunities for Young Talent	B ₅₂		
				Ensure Workforce Continuity in Emerging Technologies	B ₅₃		
		Community Engagement	B ₆	Establishment of Community Partnerships	B ₆₁		
				Strengthening Local Procurement Capacity	B ₆₂		
				Public–Private Sector Collaboration	B ₆₃		
		Communal Conflicts	B ₇	Conflicts Over Water Use	B ₇₁		
				High Environmental Costs for the Community	B ₇₂		
				Lack of Trust Between the Company and the Community	B ₇₃		
				Conflict Over Access to a Pollution-Free Environment	B ₇₄		
Environmental	C	Pollution	C ₁	Water Pollution		Seepage from Tailings	C ₁₁₁
						Contamination of Rural Potable Water Systems	C ₁₁₂
						Contamination of Groundwater and Surface Water	C ₁₁₃
				Soil Pollution		Loss of Soil Quality	C ₁₂₁
						Decrease in Food Quality	C ₁₂₂
						Accumulation of Toxic Metals	C ₁₂₃
				Air Pollution		Reduction in Greenhouse Gas Emissions	C ₁₃₁
						Reduction in Particulate Matter Emissions	C ₁₃₂
						Reduction in Visibility	C ₁₃₃
		Environmental Development	C ₂	Identify Emission Sources and Environmental Risks	C ₂₁		
				Detecting Negative Environmental Impacts	C ₂₂		
				Incorporate Climate Change Considerations in Design Phases	C ₂₃		
		Sustainable Production and Consumption	C ₃	Responsible Waste Management	C ₃₁		
				Promote the Transition to Recycling	C ₃₂		
				Extend Responsible Sourcing to Suppliers	C ₃₃		

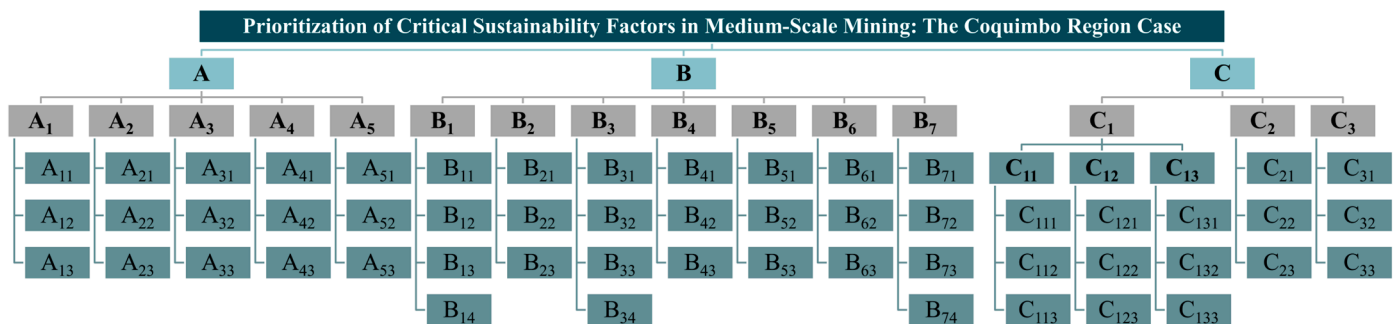


Figure 1. Hierarchical Tree.

This hierarchical model enables a systematic evaluation of critical sustainability factors, from the general goal to specific strategic actions. In this study, the alternatives and sub-alternatives correspond to targeted actions designed to improve sustainability, which are evaluated within each criterion and subcriterion.

The selection of criteria and subcriteria is grounded in the conceptualization of sustainability as an integrated system comprising economic, social, and environmental dimensions, aimed at balancing economic growth, social equity, and environmental protection over the long term [34,35]. Accordingly, the hierarchical structure of the decision model follows this three-dimensional framework, which is widely recognized in the literature, thereby ensuring the theoretical coherence of the evaluation system.

The identification and selection of the elements of the decision model were supported by a systematic literature review of scientific publications indexed in international databases, including Web of Science, SCOPUS, and SCIELO, as well as specialized Chilean sources such as Consejo Minero and SERNAGEOMIN. References were selected based on thematic relevance, focus on copper mining, applicability to the Chilean context, and relevance to medium-scale mining.

This process enabled the identification of the most recurrent and critical factors reported in the literature, which were subsequently structured into criteria, subcriteria, and alternatives. This approach ensures both representativeness of the state of the art and practical relevance, providing a robust and traceable basis for defining the evaluation system. Consequently, it reduces arbitrariness in variable selection and strengthens the validity of the proposed decision model.

3.2. Measurement Instrument

Questionnaire design constitutes a critical component in survey-based research, as the formulation of questions directly influences the quality and reliability of the results [36].

Based on the hierarchical structure, a pairwise comparison questionnaire was developed as the measurement instrument to establish priorities and was administered to an expert panel. Through expert judgment, respondents expressed the intensity of dominance or importance between elements. This process was systematically applied to all pairs of criteria, subcriteria, and alternatives. The pairwise comparison was conducted using a five-level scale, selected to facilitate expert judgment, reduce cognitive burden, and improve consistency while minimizing decision-making fatigue [37,38].

The use of a five-level scale is justified by its operational simplicity and ease of interpretation, making it particularly suitable for contexts involving numerous pairwise comparisons, as in AHP. This scale reduces cognitive complexity, promotes consistent responses, and decreases the likelihood of errors associated with respondent fatigue.

Although higher-resolution scales, such as seven-level scales, may capture more subtle differences in preferences, they increase cognitive burden and make it more difficult to

distinguish between adjacent levels. This may negatively affect the quality of judgments, particularly in settings involving a large number of pairwise comparisons. Therefore, the five-level scale represents an appropriate balance between simplicity and discriminative capacity, enabling the collection of reliable information without compromising evaluation consistency [30,39]. Accordingly, the selection of this scale prioritizes the quality and coherence of expert judgment, reinforcing model robustness over increased response granularity.

The instrument was validated by an expert panel consisting of two researchers and two professional experts in the field, ensuring clarity, relevance, and methodological consistency.

The survey was administered to an expert panel of professionals from the Coquimbo Region, selected based on their direct experience in mining management and sustainability. The panel included roles with both strategic and operational responsibilities, such as Environmental Supervisor, General Manager, Head of Engineering and Planning, Environmental Officers, Sustainability Submanager, Environmental Engineers, Environmental Permits Officer, and Community Relations Manager. This composition ensured a comprehensive perspective across technical, regulatory, environmental, and social dimensions.

Participants represented all medium-scale mining companies in the region, including Compañía Minera Teck (Carmen de Andacollo), Minera HMC S.A. (Tambo de Oro), Minera BMR SpA (Complejo Minero Punitaqui), Compañía Minera del Pacífico S.A. (El Romeral), Minera Cruz Limitada, Compañía Minera San Gerónimo, Cominor Inversiones Mineras S.A., Compañía Minera Arqueros S.A., Cuprum Resources Chile SpA, and Minera Tres Valles SpA. These operations include both open-pit and underground mining, as well as processing methods such as flotation and leaching, ensuring adequate representativeness of sectoral conditions.

Expert selection was based on criteria of specialized knowledge and decision-making experience, consistent with methodological recommendations for the AHP, thereby ensuring the validity and consistency of expert judgment.

To estimate the minimum sample size, a finite population of ten companies was considered, applying probabilistic criteria with a 95% confidence level and a 5% margin of error [40], resulting in a minimum of nine experts.

A total of fourteen experts participated, exceeding the estimated minimum sample size and aligning with the range recommended in the literature for AHP studies, typically between 7 and 15 experts [41,42].

In total, 14 questionnaires were administered, each comprising 100 questions. The resulting dataset (1400 observations) was analyzed using Expert Choice software.

4. Results and Discussion

4.1. Cronbach's Alpha

Cronbach's alpha is a widely used measure of internal reliability, assessing the consistency of responses across questionnaire items [43,44]. The coefficient ranges from 0 to 1, indicating the degree of correlation among items and whether they reliably measure the same underlying construct [45,46]. Values above 0.65 are generally considered acceptable, while values above 0.8 indicate excellent reliability [47].

In this study, Cronbach's alpha was $\alpha = 0.8611$, indicating very high reliability [48]. Results are summarized in Table 2.

In this study, Cronbach's alpha is employed exclusively to assess the internal reliability of the measurement instrument and the overall coherence of expert responses. It serves as a complementary analysis to the logical consistency evaluation inherent to the AHP. The coherence of pairwise comparisons, fundamental to AHP, is assessed through the consistency index, as described in the following section.

Table 2. Cronbach’s Alpha.

Cronbach’s Alpha	
Number of items in the instrument	100
Variance of the scores in item i	53.3018
Variance of the total questionnaire or test scores	361.4083
Cronbach’s Alpha	0.8611

Although the AHP incorporates an internal validation mechanism through the consistency ratio (CR), the use of Cronbach’s alpha is justified as an additional measure of reliability at the instrument level. This approach enables the assessment of the overall stability and coherence of responses beyond individual pairwise comparisons. Accordingly, both indicators serve complementary functions: the consistency ratio (CR) evaluates the internal logical coherence of each pairwise comparison matrix, while Cronbach’s alpha assesses the overall consistency of the set of expert judgments, thereby strengthening the methodological validity of the study.

From an applied perspective, a high Cronbach’s alpha value indicates that the model results are sufficiently reliable to support decision-making in real-world contexts. This reduces uncertainty associated with variability in expert judgment and enhances the credibility of the decision model among industrial and regulatory stakeholders.

4.2. Consistency Ratio

The consistency ratio (CR) evaluates the logical coherence of judgments for pairwise comparisons within the AHP. High consistency ratio (CR) values may indicate inconsistencies that compromise the reliability of the model results. According to Saaty’s classical criterion, consistency ratio (CR) values ≤ 0.10 are generally considered acceptable in multi-criteria decision-making [49], whereas higher values require revision of the pairwise comparison [50]. Table 3 presents the consistency ratio (CR) values obtained across the different levels of the hierarchical structure developed in this study.

However, in complex hierarchical structures involving multiple criteria, subcriteria, and numerous judgments, local deviations from this threshold may occur without compromising the overall validity of the decision model. The literature recognizes that consistency ratio (CR) values slightly above 0.10 may be acceptable, provided they do not affect structural coherence or the stability of priorities [51].

In this study, consistency ratio (CR) values exceeding the threshold are concentrated in specific pairwise comparison matrices and do not significantly affect the global priority, as verified through sensitivity analysis. This indicates that, despite local inconsistencies, the decision model maintains a robust and consistent structure at the global level.

From an applied perspective, this flexibility reflects the nature of the decision problem, where expert judgment captures real-world conditions characterized by uncertainty and multiple conflicting criteria. Accepting controlled deviations, supported by model robustness analysis, preserves the representativeness of the model results without compromising their validity.

Table 3. Consistency Ratio.

Items	Description	Hierarchy	CR	Hierarchical Structure Code
I	Prioritization of Critical Sustainability Factors in Medium-Scale Mining: The Coquimbo Region Case	GOAL	6%	GOAL
II	Economic	Criteria	11%	A
III	Mining Business	Sub-Criteria	0%	A ₁
IV	Inequalities Reduction	Sub-Criteria	0%	A ₂
V	Generation of Economic Activity	Sub-Criteria	0%	A ₃
VI	Transparent Management	Sub-Criteria	13%	A ₄
VII	Regulatory Framework	Sub-Criteria	13%	A ₅
VIII	Social	Criteria	7%	B
IX	Gender Equality	Sub-Criteria	12%	B ₁
X	Laboral Crisis	Sub-Criteria	13%	B ₂
XI	Health and Well-being	Sub-Criteria	6%	B ₃
XII	Development of Community Assets	Sub-Criteria	0%	B ₄
XIII	Education and Training	Sub-Criteria	13%	B ₅
XIV	Community Engagement	Sub-Criteria	0%	B ₆
XV	Communal Conflicts	Sub-Criteria	0%	B ₇
XVI	Environmental	Criteria	13%	C
XVII	Pollution	Subcriterion	13%	C ₁
XVIII	Water Pollution	Sub-Alternative	13%	C ₁₁
XIX	Soil Pollution	Sub-Alternative	0%	C ₁₂
XX	Air Pollution	Sub-Alternative	0%	C ₁₃
XXI	Environmental Development	Sub-Criteria	13%	C ₂
XXII	Sustainable Production and Consumption	Sub-Criteria	3%	C ₃

Therefore, the level of consistency achieved is considered adequate for the application of the AHP, supporting the reliability of the prioritization process and the robustness of the model results.

4.3. Global Priority

Figure 2 presents the global hierarchy of the evaluated Alternatives with respect to the overall objective of the study. The results indicate that Alternatives associated with the “Environmental” Criterion occupy the highest positions, concentrated in the top six ranks, despite “Environmental” and “Social” Criteria exhibiting identical global weights.

The highest-priority alternative is “Identify Emission Sources and Environmental Risks”, with a global weight of 5.3%. This is followed by “Detecting Negative Environmental Impacts” and “Promote the Transition to Recycling”, both with a weight of 3.6%. At the subsequent level, a three-way tie is observed among “Reduction in Greenhouse Gas Emissions”, “Reduction in Particulate Matter Emissions”, and “Reduction in Visibility”, each reaching a weight of 3.5%.

In contrast, the lowest-priority Alternatives are concentrated within the “Economic” Criterion. Specifically, “Operation of Processes Without Freshwater Use” (0.3%), “Preference for Sustainable Suppliers” (0.1%), and “Business Competitiveness and Profitability” (0.1%) occupy the lowest positions in the hierarchy.

Synthesis with respect to: Prioritization of Critical Sustainability Factors in Medium-Scale Mining: The Coquimbo Region Case

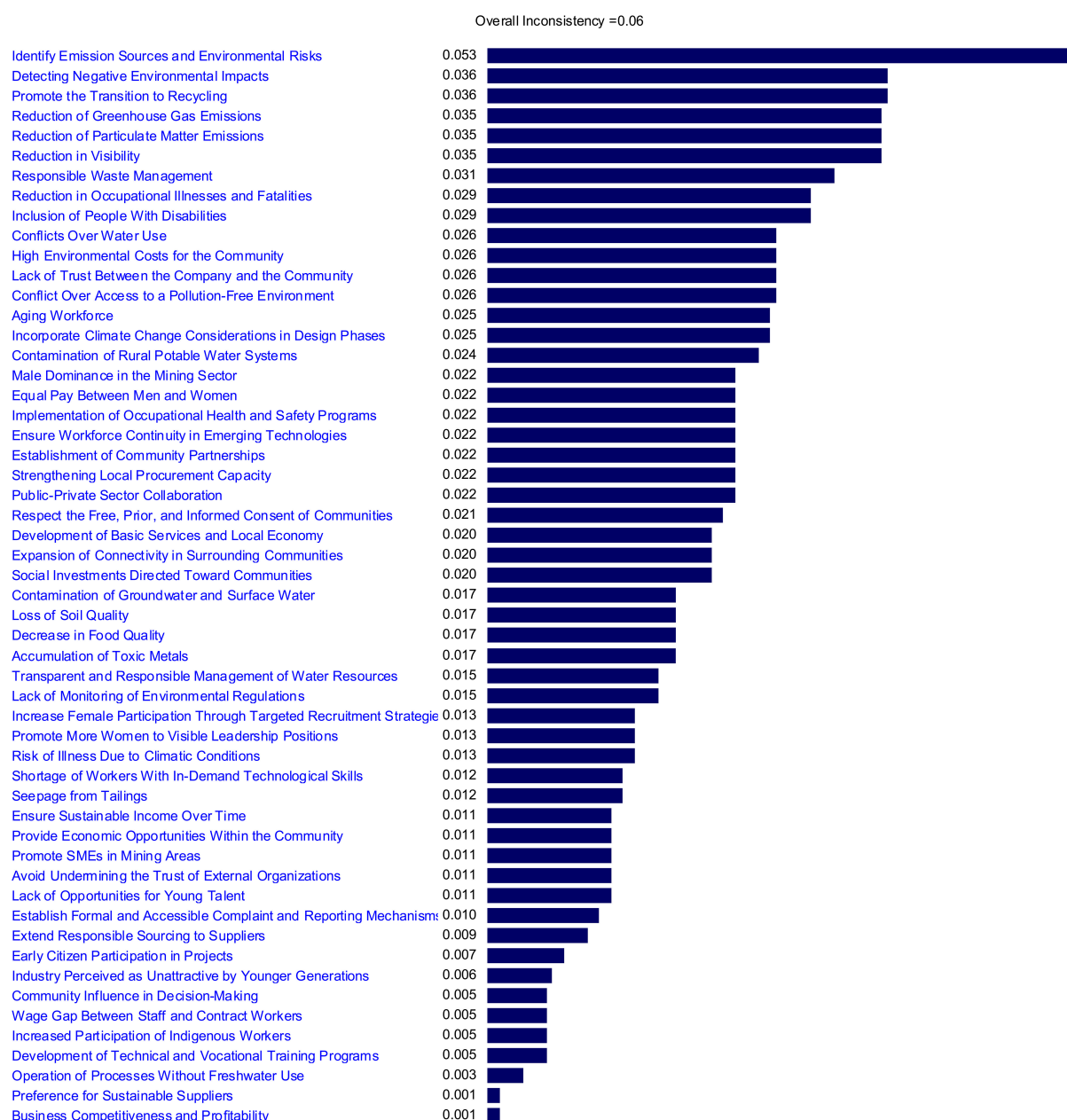


Figure 2. Global Results.

4.4. Sensitivity Analysis

Sensitivity analysis evaluates the stability of results under variations in judgments and weights within the decision model, representing a critical stage in AHP applications. This procedure systematically modifies input values to assess their impact on the global priorities of alternatives, thereby determining the robustness of the ranking. When changes in weights do not significantly alter the priority order, the results are considered stable and reliable [30,52].

In complex scenarios, small variations may affect rankings, necessitating further evaluation to ensure model coherence and facilitate expert discussion [53]. Sensitivity analysis thus reinforces result validity and enhances confidence in strategic decisions derived from the model [54].

4.4.1. Performance

For an accurate interpretation of this analysis, it is important to note that the left vertical axis represents the local priority of each alternative with respect to its corresponding criterion, while the right vertical axis indicates the global priority of each alternative. The vertical bars represent the global weight of the main criteria. Additionally, the local priority of an alternative attains its maximum value within its associated criterion and is zero for the remaining criteria.

The right-hand side of the graph presents the final ranking of alternatives according to their global priority, along with their corresponding codes, as generated by the Expert Choice software. However, due to the graphical arrangement, direct interpretation may be challenging. Therefore, the analysis should emphasize the behavior and trends of the curves rather than individual point estimates.

Two sensitivity analysis scenarios were considered to evaluate the stability of the global priority under variations in the weighting of the main criteria.

Performance Sensitivity Analysis: Case No. 1

This scenario evaluates model stability under the assumption of balanced importance among the three sustainability dimensions. The criteria Economic, Social, and Environmental were weighted equally, assigning each a priority of 33.3% (Figure 3). This scenario allows examination of the model's behavior when all three dimensions of sustainable development are considered equally relevant in the decision-making process.

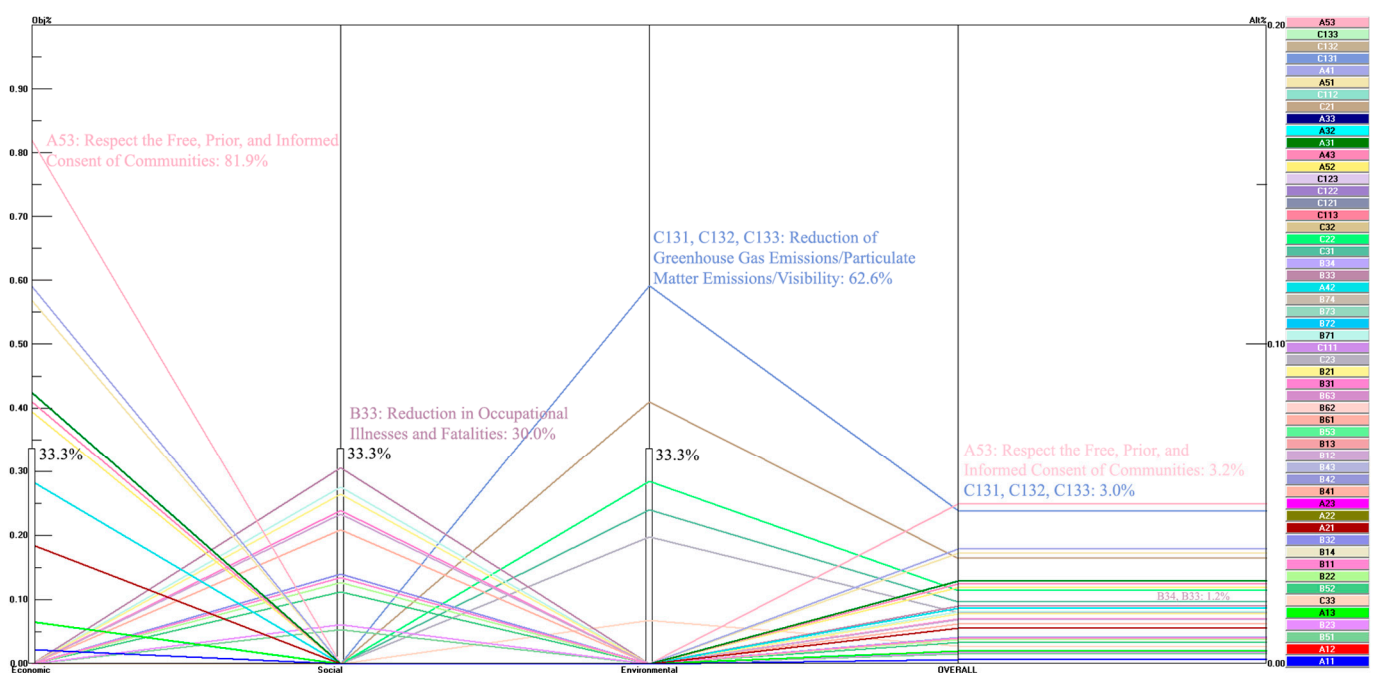


Figure 3. Performance Sensitivity Analysis Case No. 1.

The results indicate that this redistribution modifies the global hierarchy of Alternatives relative to the base case. The alternative “Identify Emission Sources and Environmental Risks” loses its dominant position, whereas “Respect the Free, Prior, and Informed Consent of Communities” significantly increases its global priority, driven by its high local weight within the “Economic” Criterion (81.9%).

Similarly, Alternatives under the “Social” Criterion experience a reduction in global priority, decreasing from approximately 2.9% to 1.2%, while those under the “Environmental” Criterion exhibit only marginal variations of around 0.5%.

Performance Sensitivity Analysis: Case No. 2

This scenario evaluates model stability under a progressive increase in the weight of the Social criterion, aiming to determine the magnitude of increase required to break the tie observed in the base case between the Social and Environmental criteria (both initially 42.9%). Since Case No. 1 demonstrated that the Social criterion is highly sensitive to reductions in weight, this analysis identifies the threshold at which a social alternative attains the highest global priority (Figure 4).

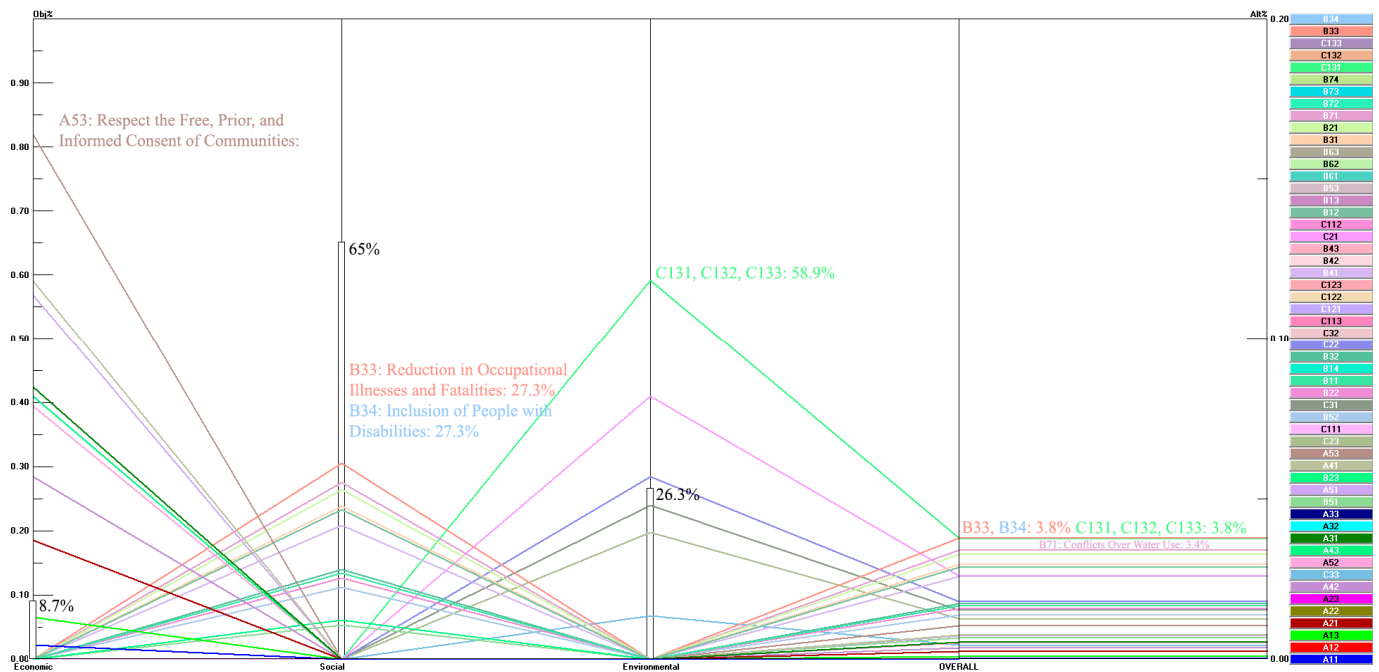


Figure 4. Performance Sensitivity Analysis Case No. 2.

The analysis further shows that an increase of approximately +22.1% in the weight of the “Social” Criterion is required for an Alternative within this Criterion to attain the top position in the global hierarchy. Under this condition, “Reduction in Occupational Illnesses and Fatalities” and “Inclusion of People with Disabilities” reach a global weight of 3.8%, equaling the Alternatives associated with the “Air Pollution” subcriterion.

Overall, this scenario suggests that, although the “Social” Criterion has a global importance comparable to the “Environmental” Criterion in the base case, its Alternatives exhibit lower local weights, which limits their capacity to displace environmental Alternatives under moderate variations in Criteria weights. This pattern reinforces the high structural robustness of environmental Alternatives within the proposed decision model.

4.4.2. Dynamic

Dynamic sensitivity analysis evaluates how global priorities change under continuous variations in criterion weights while maintaining the hierarchical model structure. This approach is particularly useful for assessing the relative stability of alternatives under extreme scenarios.

In this study, a dynamic scenario was defined by excluding the Economic criterion (weight = 0.0%), allowing the evaluation of alternatives associated exclusively with the Social and Environmental dimensions. Under this configuration, a five-way tie emerges at the top of the global priority hierarchy (Figure 5), comprising three alternatives from the Air Pollution subcriterion and two from the Health and Well-being subcriterion: “Reduction

in Occupational Illnesses and Fatalities” and “Inclusion of People with Disabilities,” each with a global priority of 4.2%.



Figure 5. Dynamic Sensitivity Analysis.

In dynamic sensitivity analysis, alternatives are displayed according to the hierarchical structure of the decision model rather than in descending order of global priority. Therefore, their interpretation should be based on the relative magnitude of their weights rather than their position within the figure.

4.4.3. Gradient

Gradient sensitivity analysis examines the stability of alternatives under continuous variations in the weighting of the main criteria, identifying intersection points at which changes in global priority occur. This approach enables the assessment of the relative robustness of both criteria and alternatives under gradual shifts in decision-maker preferences.

For proper interpretation, the horizontal axis represents variations in the weight of the criterion under analysis, while the vertical axis shows the local priority of the alternatives. Each curve illustrates how the importance of an alternative evolves as a function of these variations.

Two groups of curves can be distinguished: (i) those with a positive slope, corresponding to alternatives within the evaluated criterion, whose local priority increases as its weight increases, and (ii) those with a negative slope, associated with alternatives from other criteria, whose importance decreases due to the normalization of weights within the hierarchical structure.

The graph includes two vertical reference lines: a fixed red line representing the global priority of the criterion in the base case, and a movable dashed blue line that enables the exploration of alternative scenarios. The latter introduces a dynamic component, facilitating the identification of intersection points between curves, which indicate thresholds at which changes in ranking occur.

As these graphs are automatically generated by the Expert Choice software, the visual arrangement of curves may limit immediate interpretation. Therefore, the analysis should focus on trends, slopes, and intersection points rather than on the graphical positioning of alternatives.

Gradient sensitivity analysis evaluates the stability of alternatives under continuous variations in the weights of the main criteria, identifying the intersection points at which changes occur in the global priority hierarchy. This approach allows assessment of the relative robustness of criteria and alternatives under gradual modifications in decision-maker preferences.

In this study, three independent scenarios were analyzed, considering individual variations in the Economic, Social, and Environmental criteria.

Gradient Sensitivity Analysis: Case No. 1

Increasing the weight of the Economic criterion to 32.5% (+18.2% relative to the base case) generates a tie in the global priority hierarchy between “Respect the Free, Prior, and Informed Consent of Communities” and the alternatives in the Air Pollution subcriterion of the Environmental criterion (Figure 6).

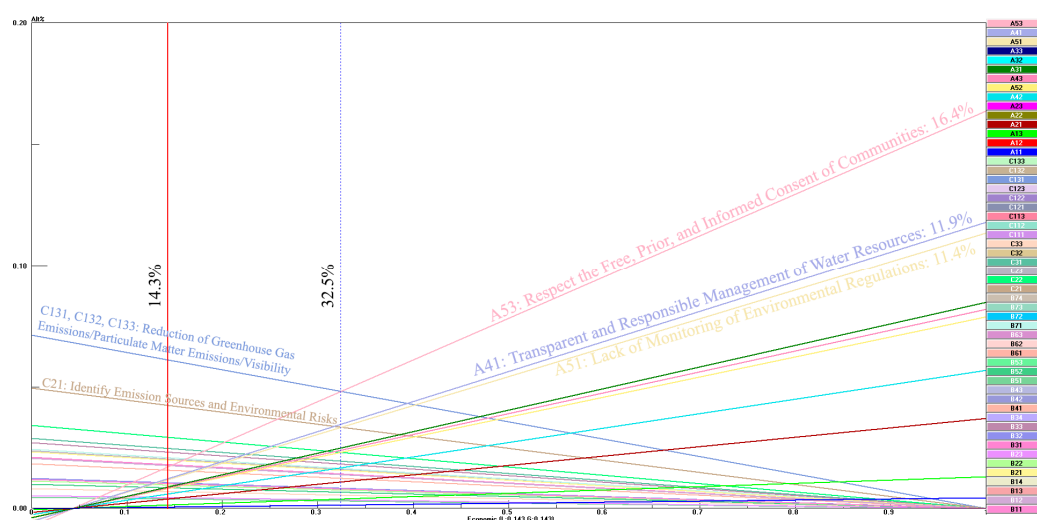


Figure 6. Gradient Sensitivity Analysis Case No. 1.

This outcome demonstrates that even with a substantial increase in the weight of the Economic criterion, environmental alternatives retain competitive positions, indicating greater relative stability under variations in criterion weighting.

Gradient Sensitivity Analysis: Case No. 2

For the Social criterion, the intersection point occurs when its weight reaches 57.4% (+14.8% relative to the base case), producing a tie between “Reduction in Occupational Illnesses and Fatalities,” “Inclusion of People with Disabilities,” and the Air Pollution alternatives (Figure 7).

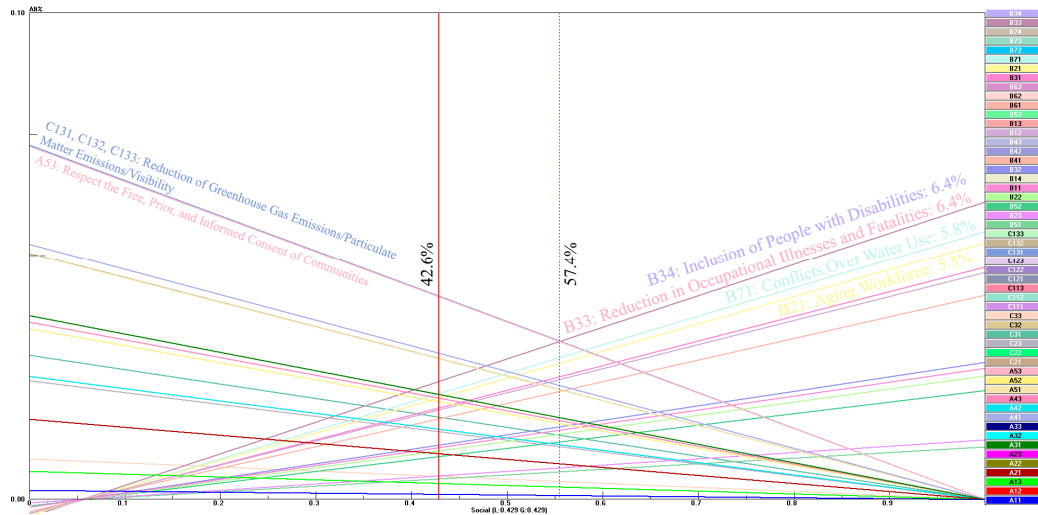


Figure 7. Gradient Sensitivity Analysis Case No. 2.

The smaller variation required to generate this tie, compared with the Economic criterion, suggests that the Social criterion exhibits greater robustness than the Economic criterion, although it remains surpassed by the structural stability of the Environmental criterion.

Gradient Sensitivity Analysis: Case No. 3

Gradient analysis of the Environmental criterion reveals a markedly different behavior. The intersection point lies to the left of the reference line, indicating that a reduction of 20.4% in its weight is required to generate a tie in the global priority hierarchy (Figure 8).

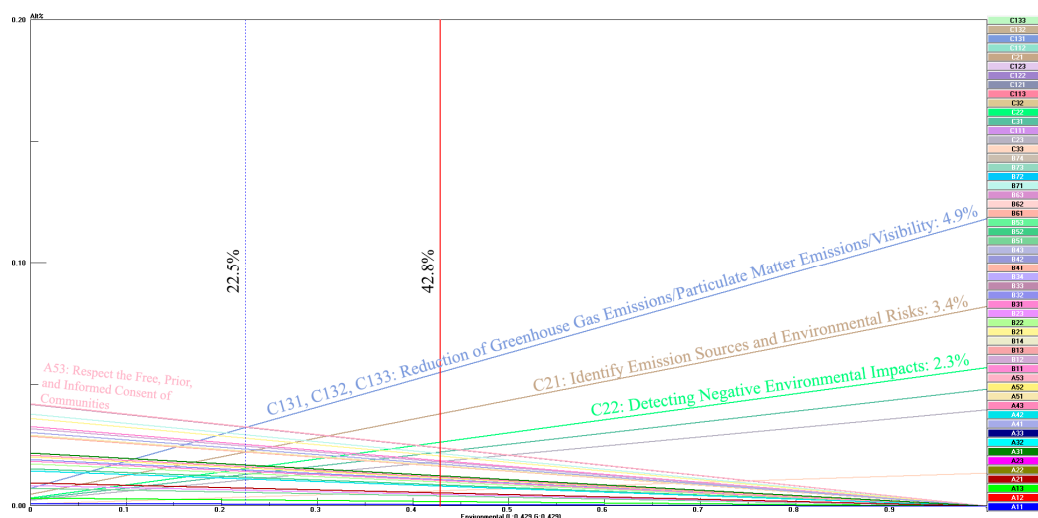


Figure 8. Gradient Sensitivity Analysis Case No. 3.

Furthermore, “Identify Emission Sources and Environmental Risks” does not appear among the top-ranked positions in this analysis, due to its relatively low local weight within the “Environmental Development” subcriterion.

5. Discussion

The results reveal a clear structural dominance of the Environmental and Social dimensions over the Economic criterion, both exhibiting a global weight of 0.429. This finding indicates that sustainability in medium-scale mining is driven less by traditional economic considerations and more by the capacity to effectively manage socio-environmental impacts. Such evidence is consistent with previous studies that highlight increasing regulatory and social pressures on the mining sector [9,10]. However, the present study advances this body of knowledge by quantitatively demonstrating how these pressures reconfigure decision-making priorities within a structured multicriteria framework.

In contrast to prior research applying MCDM methods to specific operational or technical challenges in mining [12,13], this study conceptualizes sustainability as a hierarchical and systemic decision structure. The results indicate that certain Criteria exert a dominant influence on the overall decision process, shaping the relative importance of the Alternatives beyond their individual evaluations. This directly addresses a gap in the literature, namely the limited availability of integrated approaches that combine prioritization with an explicit assessment of robustness in sustainability-related decision-making.

From the perspective of the global hierarchy, Alternatives associated with the Environmental criterion occupy the highest ranks, with “Identify Emission Sources and Environmental Risks” emerging as the top-ranked alternative. However, the sensitivity analysis enables a more nuanced interpretation: the highest-priority alternative is not necessarily the most robust. These findings challenge conventional interpretations of the AHP, suggesting that decision-making should not rely solely on static rankings but must also account for the stability of Alternatives under varying system conditions.

In particular, Alternatives associated with the subcriterion “Air Pollution” demonstrate high structural robustness, consistently maintaining dominant positions across multiple sensitivity scenarios, including performance, dynamic, and gradient analyses. This behavior suggests that atmospheric emissions management constitutes not only a priority but also a resilient strategy under changing decision contexts. Consequently, these Alternatives represent critical leverage points for the design of sustainability policies and strategies within the mining industry.

From the perspective of the working hypothesis, the results confirm that the application of the AHP enables not only the identification and ranking of critical sustainability factors, but also the evaluation of their relative stability. The principal contribution of this study, however, lies in demonstrating that decision robustness depends on the structure of the model rather than exclusively on the global weights of the Alternatives. This introduces a significant theoretical implication by shifting the analytical focus from ranking toward a structural understanding of the decision-making process.

From an applied standpoint, the findings suggest that sustainability strategies in medium-scale mining should prioritize actions that combine high importance and high robustness, particularly those related to a reduction in atmospheric emissions. Furthermore, the relevance of the Social dimension—especially in aspects such as health, well-being, and inclusion—underscores the need to strengthen policies aimed at improving relationships between mining operations and local communities, thereby supporting the consolidation of the social license to operate.

More broadly, these findings point to a transition from an extractive model centered on economic efficiency toward a structural sustainability approach, in which environmental management and social legitimacy emerge as key determinants of long-term sector viability. This transition is particularly relevant in mineral-producing regions, where pressures to increase production must be balanced against growing socio-environmental demands.

Finally, this study opens new avenues for future research on the interaction between structure and decision-making in multicriteria models. In particular, integrating the AHP with methods capable of capturing interdependencies, such as ANP or fuzzy-AHP, may provide a more comprehensive representation of complex decision environments. Future research could also evaluate the replicability of the proposed model across different mining regions or productive sectors, assessing the stability of the identified structural patterns under diverse regulatory and social contexts.

6. Conclusions

Mining activities generate a wide range of environmental and social impacts, including biodiversity loss, soil and water contamination, intensive water consumption, and adverse effects on the health of workers and nearby communities. Addressing these challenges requires mining companies to adopt sustainability strategies based on structured information, incorporating continuous monitoring, periodic impact assessment, and adaptive management with active stakeholder participation.

In the context of medium-scale mining in the Coquimbo Region, the AHP model results indicate that the “Environmental” and “Social” criteria have equal importance (42.9% each), significantly exceeding the “Economic” criterion (14.3%). This finding suggests that, according to the expert panel, sector sustainability depends primarily on balancing environmental and social dimensions rather than traditional economic factors.

The global priority analysis shows that the alternative “Identify Emission Sources and Environmental Risks” achieves the highest global weight (5.3%). However, sensitivity analysis indicates that this alternative is not the most robust under variations in criteria weighting. In contrast, alternatives associated with the subcriterion “Air Pollution,” within the “Environmental” criterion, demonstrate greater stability, maintaining high ranking positions under significant changes in the hierarchical structure. Within the “Economic” dimension, the most relevant alternative is “Respect the Free, Prior, and Informed Consent of Communities,” while within the “Social” criterion, “Reduction in Occupational Illnesses and Fatalities” and “Inclusion of People with Disabilities” are particularly prominent. These results highlight the importance of complementing the traditional AHP ranking with sensitivity analysis to avoid decisions based solely on the base case.

These findings demonstrate that prioritization based exclusively on global priority may be insufficient in complex contexts. Incorporating sensitivity analysis is therefore essential to evaluate the structural stability of decisions. A key contribution of this study is demonstrating that combining the AHP with sensitivity analysis enables not only the identification of priorities but also the evaluation of their robustness under changing conditions.

From an applied perspective, the results indicate that strategies aimed at reducing atmospheric emissions should be consistently prioritized due to their stability across scenarios. The proposed decision model also supports efficient resource allocation by prioritizing investments in actions that combine high global priority and model robustness, while contributing to strengthening the social license to operate.

From a scientific perspective, this study addresses a gap in the literature concerning the limited integration of multi-criteria prioritization and model robustness analysis in mining sustainability assessments. Unlike conventional approaches, the proposed decision model not only structures economic, social, and environmental criteria but also incorporates performance, dynamic, and gradient sensitivity analysis, providing a more comprehensive understanding of the decision system.

Furthermore, the approach introduces a structural perspective on decision-making, in which the performance of alternatives depends not only on their global weights but

also on their interaction with the architecture of the decision model. This enables a more comprehensive and realistic interpretation of results in complex decision contexts.

Finally, it is recommended that sustainability strategies for medium-scale mining in the region prioritize the mitigation of environmental impacts—particularly air pollution—while strengthening social dimensions that support the acceptance and legitimacy of mining activities.

Despite its methodological robustness, this study has limitations. The expert panel is restricted to medium-scale mining in the Coquimbo Region, which may limit the generalizability of the model results to other contexts. In addition, the analysis relies on expert judgment, which, although supported by consistency verification and sensitivity analysis, inherently involves subjectivity.

Future research should extend the decision model to other mining regions and compare results across different operational scales. Moreover, integrating the AHP with other multi-criteria decision-making methods, such as the Analytic Network Process (ANP) or fuzzy AHP, would enable the incorporation of interdependencies among criteria and a more explicit treatment of uncertainty in complex mining decision contexts.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
α	Cronbach's Alpha (measure of internal reliability)
CI	Consistency Index
CR	Consistency Ratio
ESG	Environmental, Social, and Governance
GOAL	Overall Goal in AHP Hierarchy
MCDM	Multi-Criteria Decision-Making
$\lambda_{\max}$	Maximum Eigenvalue of Pairwise Comparison Matrix
RI	Random Index
SDGs	Sustainable Development Goals
SMEs	Small and Medium-Sized Enterprises

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